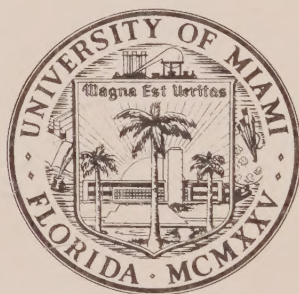


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RENDICONTI

DELLA

SCUOLA INTERNAZIONALE DI FISICA

« ENRICO FERMI »

Varenna, Italy. Scuola internazionale di fisica

SOCIETÀ ITALIANA DI FISICA

RENDICONTI

DELLA

SCUOLA INTERNAZIONALE DI FISICA
« ENRICO FERMI »

CORSO XII

Direttore: G. RIGHINI

VARENNA SUL LAGO DI COMO

VILLA MONASTERO

15-30 LUGLIO 1959

RADIOASTRONOMIA SOLARE

NICOLA ZANICHELLI - EDITORE

BOLOGNA

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INTRODUZIONE

Parole inaugurali

DI

G. POLVANI

Presidente della Società Italiana di Fisica

Dopo il Corso di Termodinamica dei processi irreversibili, dopo quello sulle cosiddette Interazioni deboli, ecco oggi iniziarsi, terzo dell'annata, il Corso sulla Radioastronomia solare; e, come per quelli, ecco svolgersi la breve cerimonia inaugurale: atto che si ripete per la XII volta, perchè il dodicesimo è questo Corso della serie iniziata, dalla nostra Scuola Internazionale di Fisica, nell'ormai lontano 1953.

La direzione del Corso è affidata al Direttore dell'Osservatorio Astrofisico di Arcetri, il prof. GUGLIELMO RIGHINI, che già qui conoscemmo un anno fa per avere egli organizzato e diretto il Corso di Fisica del plasma nei fenomeni astrofisici, e che, nonostante le sue numerose occupazioni, si è con grande impegno dedicato all'organizzazione di questo Corso di cui da oggi assume la Direzione.

Intorno a lui sono e con lui hanno assunto il carico delle lezioni, il prof. R. COTTREZ dell'Osservatorio Reale di Uccle nel Belgio, il prof. C. DE JAGER dell'Osservatorio Astronomico di Utrecht in Olanda, il prof. O. HACHENBERG dell'Istituto Hertz di Berlino Est, il prof. K. O. KIEPENHEUER del Fraunhofer Institut di Friburgo in Breisgau in Germania, il prof. M. MINNAERT dell'Osservatorio Astronomico di Utrecht in Olanda, il prof. G. TORALDO DI FRANCA dell'Università di Firenze, il prof. J. P. WILD del Consiglio delle Ricerche Australiano di Sydney in Australia.

A tutti i professori che ho nominato vadano da parte della Società Italiana di Fisica, del Consiglio di essa e specie da parte mia il benvenuto più cordiale e le espressioni della più viva riconoscenza per il lavoro cui si sobbarcano. A tutti, ho detto; ma particolarmente al prof. RIGHINI che non ha esitato di assumere per la seconda volta, pur già conoscendo dalla prima la fatica cui andava incontro, il compito della organizzazione e della direzione del Corso.

E ugualmente il benvenuto vada agli allievi. Essi sono: F. BACHELET 'di Roma, D. CATTANI e M. CECCARELLI di Bologna, T. DE GROOT di Utrecht in Olanda, J. T. DE JAGER di Dwingeloo in Olanda, G. ELSTE di Gottinga in Germania, A. D. FOKKER dell'Aia J. KLECZEK di Andrejov in Cecoslovacchia, A. M. MALINGE di Meudon in Francia, G. MANNINO di Bologna, G. NOCI e M. PIATTELLI di Firenze, H. H. RABBEN di Freiburg in Breisgau in Germania, M. SCHMORAK di Rehovot in Israele, G. SETTI di Bologna, P. SIMON di Parigi, R. STEINITZ di Jerusalem in Israele, H. TANAKA di Nagoya in Giappone, R. VISOCEKAS di Parigi, D. J. H. WORT di Harwell in Inghilterra.

Relativamente pochi — si potrebbe osservare — sono gli allievi: venti in confronto dei quarantaquattro, per esempio, del corso precedente. Ciò non proviene dal minore interesse o dalla minore importanza del Corso, ma solo dall'essere questo ramo dell'Astrofisica, la Radioastronomia solare, particolarmente circoscritto e quasi all'inizio del suo sviluppo: eppure quante e quali meraviglie essa già abbia rivelato o di quante e quali meraviglie si mostri ripiena vi potrà illustrare tra breve il prof. RIGHINI.

Qui io desidero sottolineare l'importanza, ovvia del resto, che il poter tenere un Corso siffatto riveste. E poichè questa possibilità proviene sostanzialmente dagli aiuti dati alla nostra Scuola Internazionale di Fisica, vorrei proprio rinnovare — come nel fatto rinnovo calorosissimi — i ringraziamenti verso gli enti e le persone che con il loro contributo finanziario o con altri aiuti hanno reso possibile anche quest'anno la vita della nostra Scuola.

Queste persone e questi enti già nominai nelle mie brevi parole inaugurali del I Corso di quest'anno: debbo oggi, con piacere, aggiungere alla lunga lista allora resa nota, il nome della Sig.ra dott. TERESA MATEROSI MAGRI di Brescia, già nostra bravissima allieva all'Istituto di Fisica di Milano.

A tutti, ripeto, un grazie di cuore.

* * *

Il compito che questo mio breve discorsetto inaugurale doveva assolvere, si compie ormai, dopo quanto ho detto, dichiarando aperto il III Corso 1959, XII della serie, relativo alla Radioastronomia solare, ed augurando ad esso il migliore successo.

Prolusione al Corso.

DI

G. RIGHINI

Direttore del Corso

Il Corso che quest'anno ho l'onore di dirigere è un logico seguito al corso di Fisica del plasma effettuato nel 1958. Infatti la Radioastronomia si occupa dello studio delle onde elettromagnetiche emesse dai plasmi solari ed interstellari ed è in questo senso che si può dire che quest'anno noi siamo qui riuniti per studiare a fondo una parte del vasto campo abbracciato dalla Fisica del plasma.

Ancora una volta vediamo qui riuniti specialisti dell'Astrofisica ottica e dell'Astrofisica hertziana poichè mentre la seconda indaga e studia nuovi fenomeni, è sulla base dei risultati della prima che si può giungere ad una corretta interpretazione dei fenomeni stessi.

È per me un grato dovere dare il benvenuto al gruppo dei docenti che hanno cortesemente accettato la non lieve fatica di tenere le lezioni ed agli allievi qui convenuti per apprendere ed aggiornarsi sui risultati più recenti della Radioastronomia solare.

Abbiamo con noi quest'anno tre eminenti fisici solari: il padre della fisica solare moderna, il prof. MINNAERT di Utrecht ed il suo valoroso allievo, il dott. DE JAGER; ed il prof. KIEPENHEUER che si può dire ormai persona di famiglia qui a Varenna dato che ha partecipato già a vari corsi.

La celebre scuola dei radiofisici australiani ci ha mandato uno dei suoi più autorevoli rappresentanti, il dott. WILD inventore del radiospettrografo che tanto ha contribuito alla conoscenza dei fenomeni del sole attivo.

Del gruppo ben noto di ricreatori di Uccle abbiamo con noi il dott. COUTREZ che in realtà rappresenta il ponte di collegamento fra Radiofisica e Fisica solare in quanto essendo inizialmente un fisico solare si è successivamente specializzato nella Radioastronomia organizzando e potenziando il ben noto radioosservatorio di Humain-Rochefort nelle Ardenne.

Ma poichè entro la Radioastronomia vi sono pure delle specializzazioni do-

vute soprattutto all'indirizzo tecnico, abbiamo invitato qui per aggiornarci sugli studi delle onde centimetriche solari il dott. HACHENBERG dell'Istituto Hertz di Berlino.

I due gruppi di lezioni che riguardano la Fisica solare e la Radioastronomia hanno però una base in comune: le onde elettromagnetiche.

Le lezioni fondamentali sulla Teoria delle onde elettromagnetiche saranno svolte dal prof. TORALDO di Firenze che come è noto è uno specialista sia nel campo dell'Ottica che in quello della Fisica delle onde hertziane.

Oltre alle lezioni il programma lascia il tempo libero per colloqui, discussioni e contatti personali.

Mi auguro che questo Corso possa contribuire ad un maggiore sviluppo delle ricerche di Radioastronomia solare specie nel nostro paese e che la vita in comune qui in questa magnifica cornice naturale sia fonte di nuove e solide amicizie e di una proficua collaborazione fra gli studiosi qui convenuti.

SCUOLA INTERNAZIONALE DI FISICA «E. FERMI»

NEL CORSO VARENNÀ SUL LAGO DI COMO - VILLA MONASTERO 13-19 Luglio 1958



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5. R. Visoczek
6. P. Simon
7. D. J. H. Wort

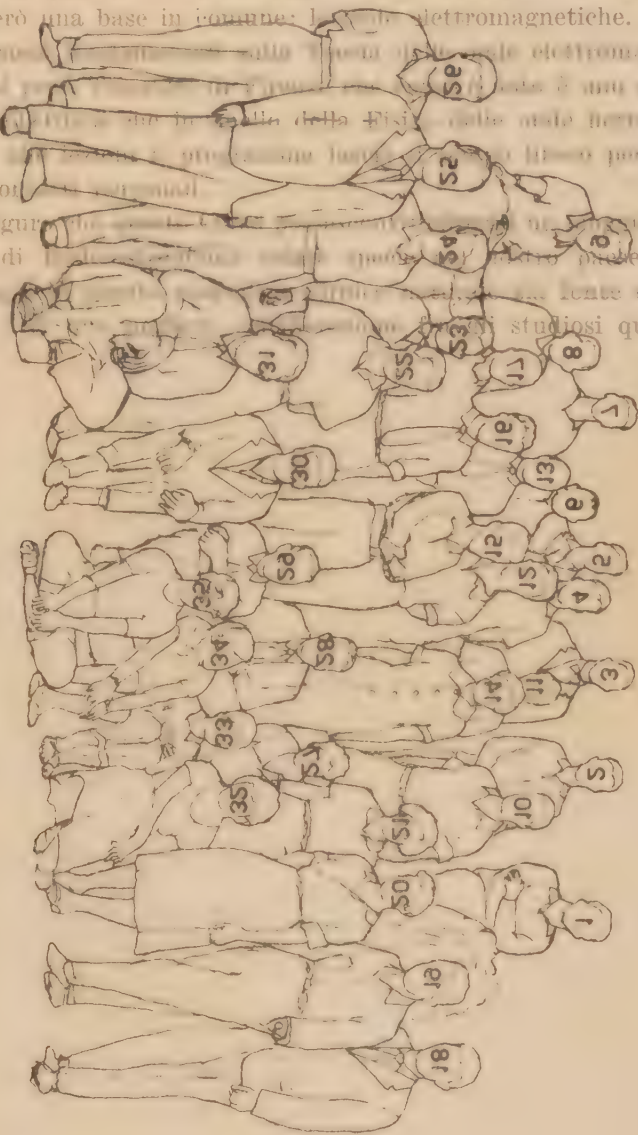
8. M. Minnaert
9. M. Schmorak
10. R. Steinitz
11. C. Zecchinato
12. J. Kleczek
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14. F. Bachelet

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16. J. T. de Jager
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33. I. Toraldo
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studi delle onde centimetriche solari il dott. HACHENBERG dell'Istituto
 di Berlino.

però una base in comune: l'elettromagnetismo.

elettromagnetismo saranno

e con

e che la vita in

studiosi qui convenuti.

SOCIETÀ ITALIANA DI FISICA

SCUOLA INTERNAZIONALE DI FISICA « E. FERMI »

XII CORSO - VARENNA SUL LAGO DI COMO - VILLA MONASTERO - 15-30 Luglio 1959



LEZIONI E SEMINARI

General Survey on Solar Phenomena.

M. MINNAERT

Sterrewacht Sonnenborgh - Utrecht

I. — The Undisturbed Sun.

Introduction.

Solar Physics is a widely studied science with an extensive literature, and it is really impossible to summarize in a few lectures the whole of this discipline! It will be necessary to leave aside all technical explanations concerning the methods of research, to postpone most of the radio investigations, to make a choice between different possible theories, to skip names of authors and references. We shall simply try to picture the sun as it really is and to present a model of the solar phenomena.

In the course of this survey, it will be interesting to inquire at each step in how far the structure of this celestial body is uniquely determined by its mass and chemical composition. We shall see that this is really the case and that we are able, already now, to understand the general structure and motions in the sun as simple consequences of the physical laws. The explanation of the detailed solar disturbances, however, is often difficult but progresses quickly.

1. — The deep interior.

1.1. *The origin of the sun.* — So as the other stars, the sun has developed from a cloud of interstellar gas and dust, forming first a *protostar*, which contracted further by the action of gravitation. As soon as the protostar becomes opaque, the contraction takes place adiabatically, and after $3 \cdot 10^7$ years the temperature in the central parts becomes so high, that the nuclear reactions

come into play. By then, most of the rotational moment has been dissipated through the magnetic coupling between the star and the surrounding ionized cloud. The sun has now a mass of $2 \cdot 10^{33}$ g; it settles on the main sequence and develops very slowly. All this happened about $5 \cdot 10^9$ years ago.



Fig. 1. The sun with spots, photographed in white light. Radius: 700 000 km. Catania Observatory.

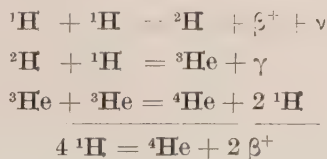
From the equations, describing the stellar interior, it is found that the outer parts of the sun are in convective motion, while the interior parts are in radiative equilibrium with hardly any mixing. In the course of the evolution, the central parts will be partly depleted of their hydrogen, which has been transformed into helium. Perhaps the most plausible model of the present sun is as follows:

Original composition	Present composition		Boundary rad.-conv.	Center
	Center	Convective envelope		
$X = 0.78$	0.30	0.78	$R = 0.82 R_{\odot}$	$R = 0$
$Y = 0.20$	0.68	0.20	$T = 1.2 \cdot 10^6 \text{ }^{\circ}\text{K}$	$15 \cdot 10^6 \text{ }^{\circ}\text{K}$
$Z = 0.02$	0.03	0.02	$\rho = 0.04$	130
(X = hydrogen content by mass, Y = helium content, Z = heavier elements.)				

The fraction 0.997* of the mass is in radiative equilibrium. It is assumed that the material in the outer layer has still the unchanged original composition.

A special problem is connected with the Li content of the sun, which is much smaller than on earth; this has been often explained, by assuming that part of this element has passed through deeper layers and has been transformed by neutron bombardment. However from the model just described it is clear that the temperature, even at the bottom of the convective layer, would not be sufficient for such a transmutation. It is therefore assumed that the lithium was already partly transformed during the last contraction phase of the protostar.

At the temperature of the solar center, the main nuclear reaction chain is the proton-proton cycle



with the secondary reactions

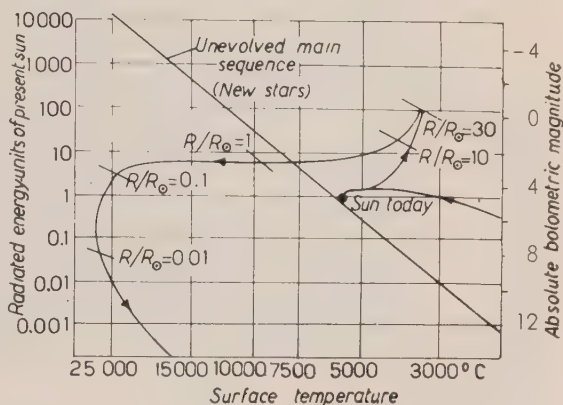
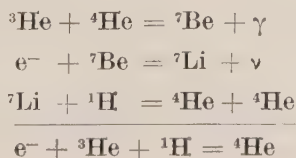


Fig. 2. - The evolution of the sun. Adapted after SANDAGE: *Amer. Journ. Phys.*, **21**, 525 (1957).

Mereover a very small contribution is due to the CN-cycle (4% in the center of the sun).

Because of these nuclear reactions, the sun radiates and is blown up to a certain volume. Even taking account of the secondary reactions, the calculated rate of energy production is not yet sufficient to explain the present value of the solar radius: some nuclear cross-sections will probably have to be modified.

1'2. *The convection zone.* — The state of equilibrium in a stellar atmosphere is determined by the way in which the temperature T decreases with the height h .

When a model of the solar interior is calculated, it is found that in the outer zone the inequality prevails:

$$\left(\frac{dT}{dh}\right)_{ad} < \left(\frac{dT}{dh}\right)_{rad},$$

which means that convective motions will develop. Theories of convection in general relate to a quasi incompressible atmosphere. But they have not yet been developed for such a zone, in which the density varies by a factor of 10^4 . The main problem is, to estimate the size of the turbulent elements, which may be put equal to the *mixing length*.

For this, two theories have been given:

1) It has been generally assumed, that this mixing length is of the same order as the local scale-height of the

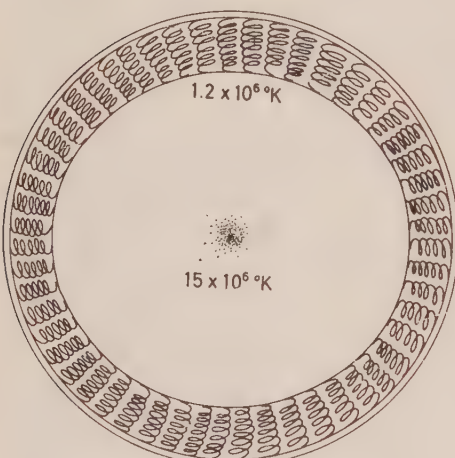


Fig. 3. — The interior of the sun. Central core, ellipsoidal zone in radiative equilibrium, convective shell, photosphere.

atmosphere. The model of the solar interior is very sensitive to the assumption made, and requires that the mixing length be put equal to 1.5 times the scale-height.

2) On the other hand, due to the ionization of hydrogen the driving force for convective motion $(dT/dh)_{rad} - (dT/dh)_{ad}$ is about 100 times greater in the very unstable top layer of the convection zone, with a thickness of about 500 km, than in the lower layers. This determines the size of the turbulent elements in the top layer.

This size being given, all conditions inside the convective layer may be calculated: the velocity of ascension of the turbulent elements, their lifetime,

the temperature gradient inside such an element and inside the medium, etc. This gives a complete theory of the granulation.

13. *Observations about the convection in the photosphere.* — It follows from different sources of information, that the photosphere is not homogeneous.

1) Near $\tau = 1$. Direct observation of the solar surface, in white light, shows a tiny *granulation*. In order to avoid the imperfections of seeing, photo-

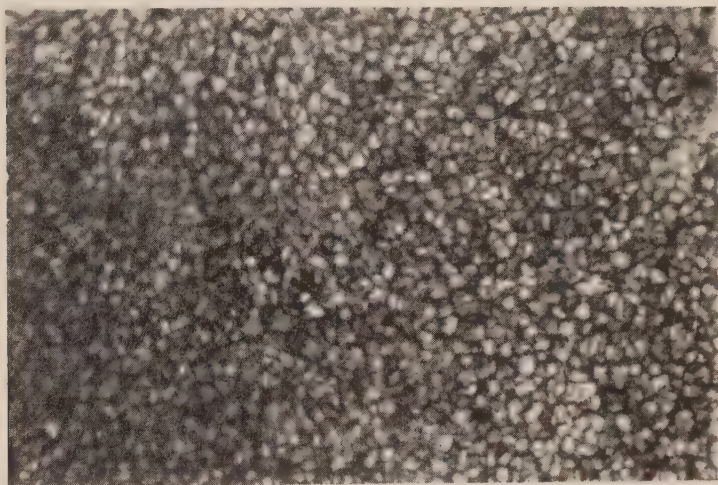


Fig. 4. — The granulation, photographed from a height of 25 km. SCHWARZSCHILD, *Astrophys. Journ.*, **130**, 345, (1959).

graphs have been taken from a balloon, at heights up to 25 km. The size of the granules varied from $0''.3$ to $2''.5$, with a mean value of $1''.0$ — 700 km. From the photometry: $\sqrt{(\Delta i/2)} = 0.07$, corresponding to $\Delta T = 170^\circ$. The life-time of the granules is $(1 \div 10)$ min.

2) Near $\tau = 0.2$. Zigzag structure of the Fraunhofer lines, observed especially clearly in the vacuum spectrograph. Apparently the spectra of the individual granules are slightly shifted with respect to each other because of Doppler effects: $v_{\text{rad}} = (0.4 \div 1.5)$ km/s.

3) Near $\tau = 0.1$. The Fraunhofer line profiles show the effects of *microturbulence* by their profiles, which are broader and have more the sharp V form than pure thermal motion would explain; by their asymmetry or wavelength shifts they also show the effect of *macroturbulence*. Some recent models

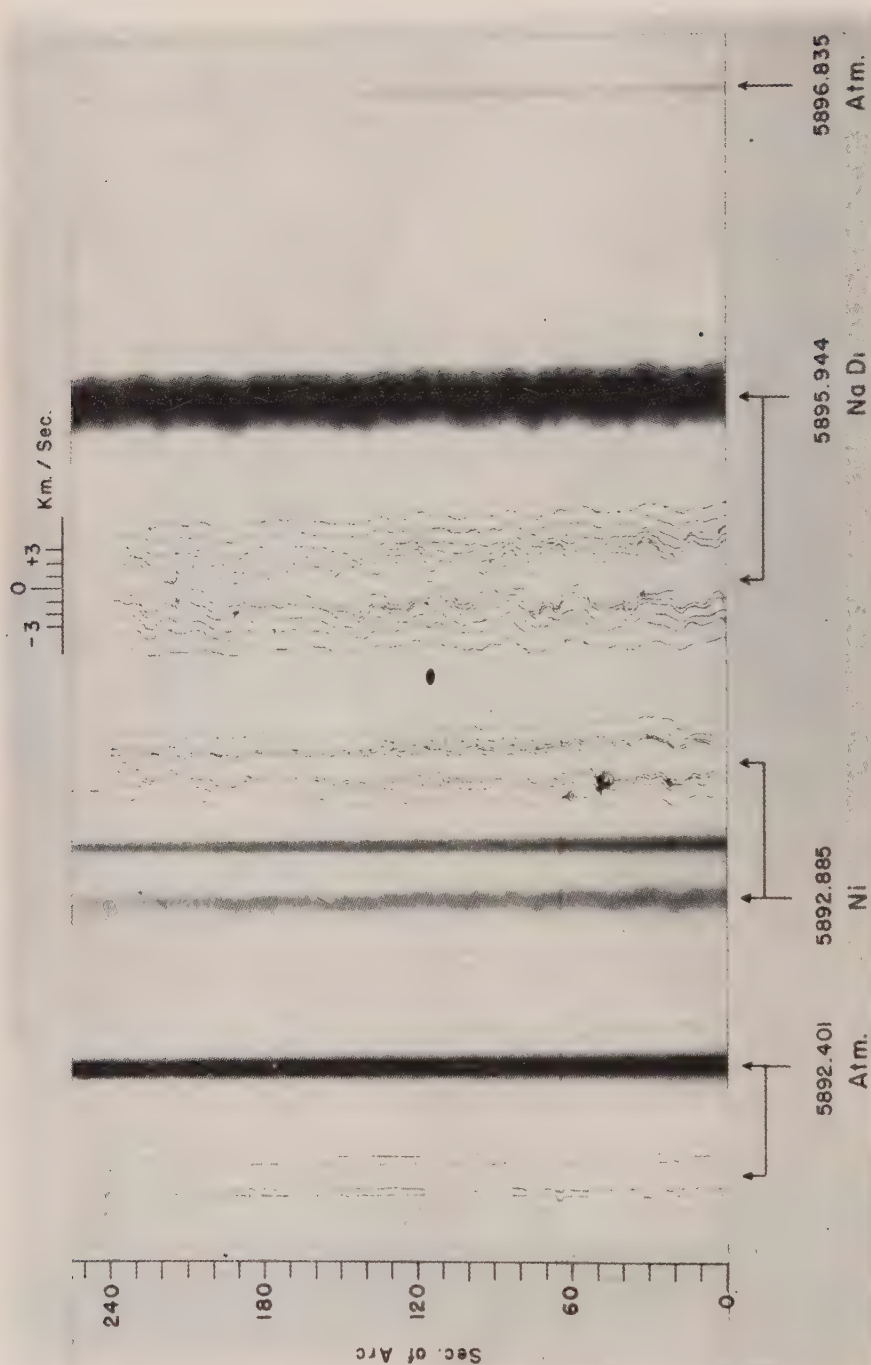


Fig. 5. Zigzag structure of the Fraunhofer lines. The Ni and Na lines show the characteristic whiggles; the terrestrial atmospheric lines are straight. (After McMATH, MOHLER, KEITH PIERCE: *Astrophys. Journ.*, 122, 566 (1955)).

would require a brightness difference $\Delta i/i = 0.45$ between each granule and the background, with $v_2 = (1.5 \div 3)$ km/s; this seems exaggerated, if the observations of the granulation are reliable.

1'4. *The solar rotation.* — From the observation of the details at the solar surface, it is found that the angular velocity depends on the latitude, according to the formula

$$\xi = 14^{\circ}.38 - 2.77^{\circ} \sin^2 \varphi.$$

Even the corona takes part in this general rotation.

This remarkable law may be explained by taking into account the internal structure of the sun. The inner part, which is in radiative equilibrium, must rotate almost as a rigid body with uniform angular velocity, because of its high viscosity. Convection transports momentum in a radial direction through the outer, convective envelope. The observed law of surface rotation may be explained, by assuming that the radiative core has the shape of an ellipsoid with $b/a = 0.92$ and an angular velocity of $19^{\circ}/\text{day}$, still about the same as its original value

It has been shown theoretically, that slow meridional currents must develop in the convective envelope. A few observational data give evidence on this question:

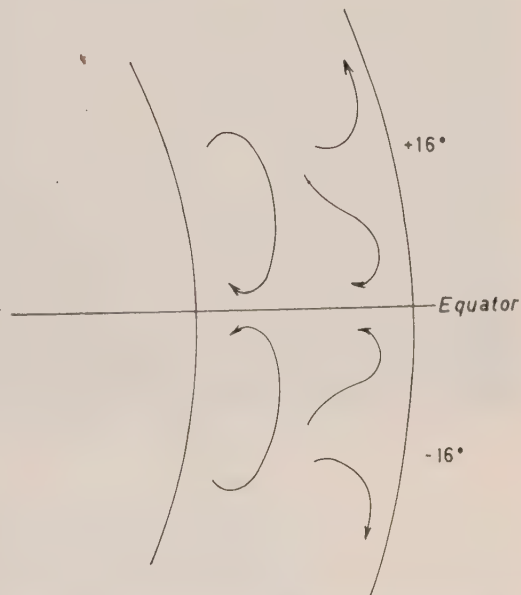


Fig. 6. Meridional section through the outer parts of the sun.

a) there is a general latitude drift of the sunspots, those above $|\varphi| = 16^{\circ}$ drifting away from the equator, those below $|\varphi| = 16^{\circ}$ drifting towards the equator;

b) in each 11-year period, the sunspots are formed first in a high latitude, later in lower and lower latitudes;

c) there are indications from the solar spectrum, that the temperature at the poles of the sun is slightly higher than at the equator.

15. *The general magnetic field.* — With the magnetograph, it is possible to scan the solar surface for magnetic fields: the instrument is based on the observation of the very slight polarization in the wings of Fraunhofer lines, due to the Zeeman effect. Such instruments are in use at the Mt. Wilson Observatory (already during a complete 11-year period), at Potsdam and at the Crimean Observatory. Fields of 0.3 oersted are just measurable.

The magnetic fields at the solar surface are very complicated; but beyond $\varphi = 55^\circ$ on both hemispheres a general field is found to exist, the polarity being

opposite to that of the earth. From observation of the pole bushels of the corona, it appears that the magnetic axis coincides with the rotation axis. The general field in the line of sight is of the order of 1 oersted.

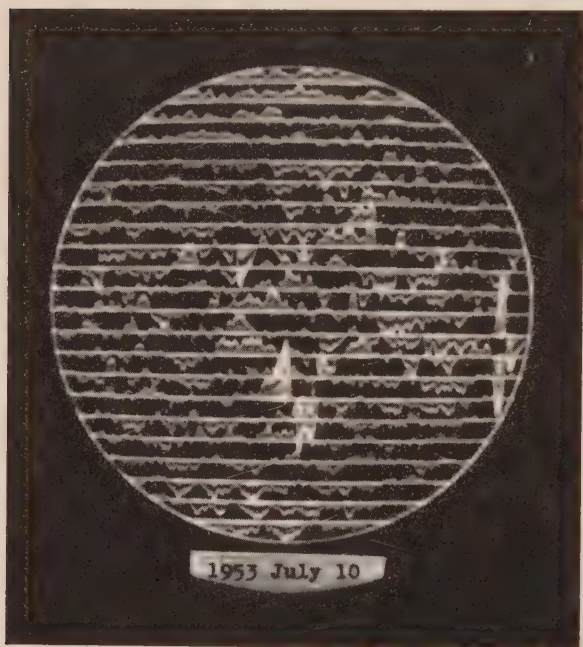


Fig. 7. — Magnetoheliogram, showing local fields near spots and faculae; near the poles the general magnetic field becomes visible. The deflection of the spot from the fiducial line, upwards or downwards, corresponds to S or N polarity. (Obtained by H. W. BABCOCK: Mt. Wilson Observatory).

2. — The photosphere.

The huge gaseous sphere, which we call the sun, is limited at the outside by a layer, dense enough in order to emit a continuum radiation and to show a considerable brightness, and still sufficiently transparent to allow a direct investigation. This layer, deep by about 300 km, is called *the photosphere*.

Speaking about the solar *atmosphere*, we intend to designate the whole of all layers which we are able to look through; this includes also the chromosphere and the corona.

The photosphere is the best investigated part of the sun, of which the theory has reached a high degree of mathematical and physical perfection. Starting from a preliminary investigation of the solar radiation, we derive almost

without any astrophysical theory the total flux and the approximate chemical composition. From these data we are able to explain all observations about the solar radiation and to give a better interpretation of the solar spectrum, better data on the chemical composition and a detailed photospheric model. The whole investigation proceeds by successive approximations.

The total radiation, measured outside the atmosphere, amounts to $2.00 \text{ cal/cm}^2 \text{ min}$, corresponding to an effective temperature of 5785°K . The results of the radiation measurements at sea level, corrected for atmospheric extinction in a refined way, are now in good agreement with the results from rockets and in rather good agreement with those from sounding balloons (1.96 cal).

The energy-wavelength curve may be given *a*) for the real continuous background of the spectrum; *b*) for the smoothed energy curve, modified by the numerous Fraunhofer lines. It resembles more or less a black body curve for a temperature of the order of 6000° . Near $\lambda = 3647$ the Balmer jump is observed: $D = \log(E^+/E^-) = 0.13$.

The energy distribution is described by a different color temperature at each side of this limit: $T^- = 6225^\circ$; $T^+ = 7540^\circ$. It is a happy but accidental circumstance, that such a representation is possible. Actually the radiation observed in each wavelength is the sum of the contributions of all the various

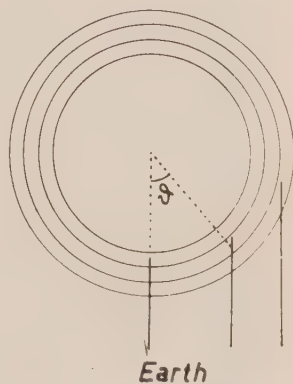


Fig. 8. Explanation of the limb darkening.

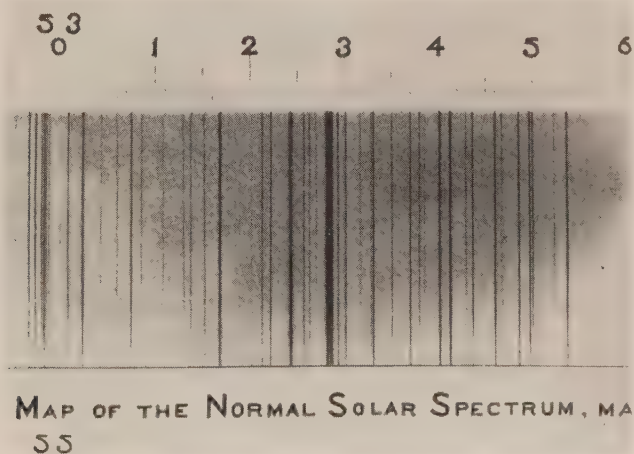


Fig. 9a. — Part of the Rowland map of the solar spectrum. Near $\lambda = 5324$ and 5328 strong Fe lines.

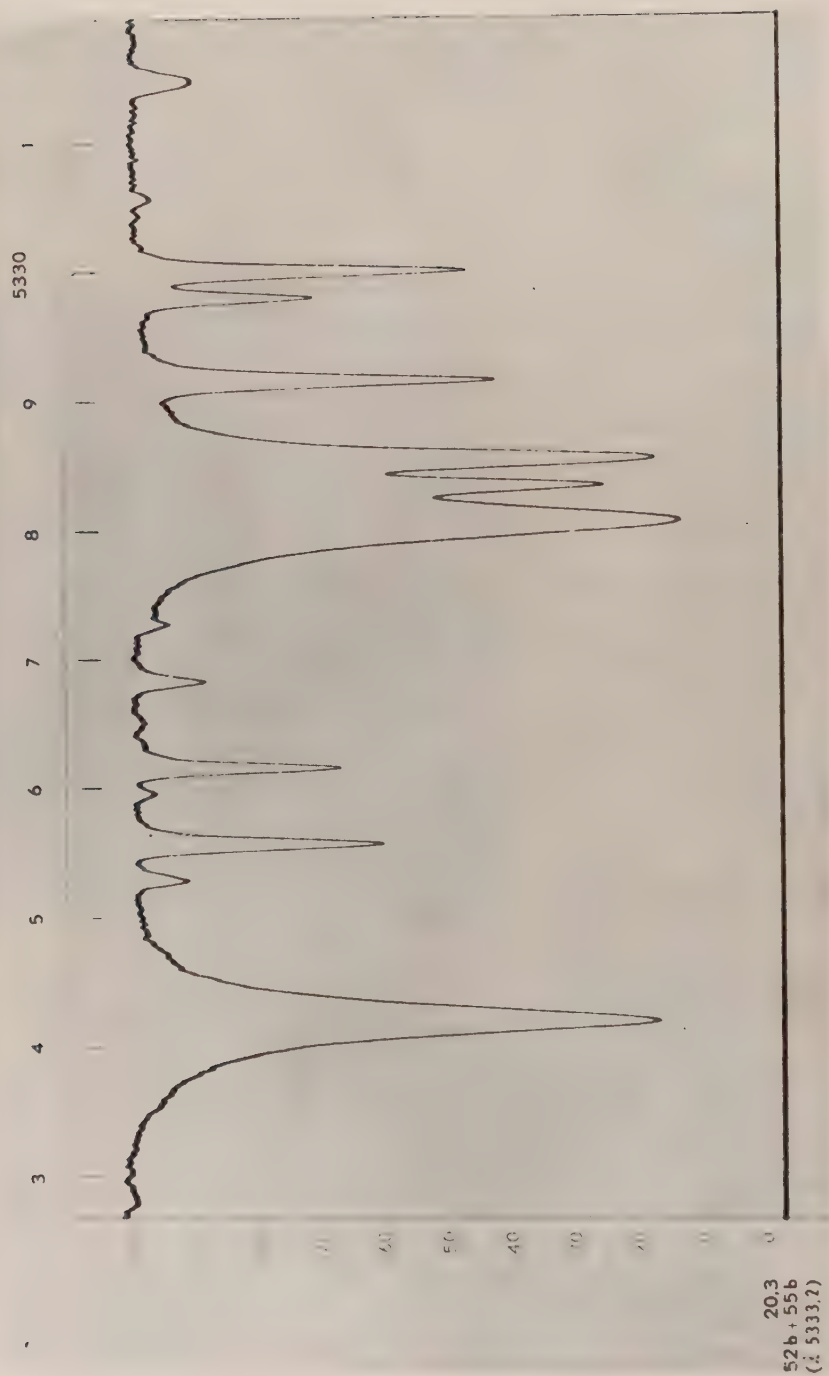


Fig. 9b. Record of the same lines in the Utrecht Photometric Atlas.

photospheric layers at different temperatures, each of them being weakened by the total absorption of all the exterior layers.

The brightness of the sun's disc decreases towards the limb; this effect is the more pronounced the shorter the wavelength. It is due to the inward temperature increase of the photospheric layers. The radiation near the limb has its origin in higher layers than the radiation observed near the center of the disc. This relation applies to almost all solar phenomena and is generally used in order to investigate how the conditions inside the solar atmosphere vary with depth. Approximately the distribution of the brightness may be represented by

$$\frac{i}{i_0} = 1 - u + u \cos \vartheta,$$

where ϑ is the heliocentric angle between the center

of the disc and the observed area. The brightness at the extreme limb can be determined only with difficulty; eclipse observations are useful.

The solar spectrum is a spectrum of dark lines on a continuous background. It is generally studied with large scale grating spectrographs; interferometers are only used for special problems. The Rowland photographic atlas is extremely useful, especially in combination with the Revised Rowland Table. The Utrecht Photometric Atlas extends from 8700 to 3610 Å (Appendix unto $\lambda = 1300$); a photometric catalogue is in preparation. Towards the infrared: the atlas and catalogue of the McMath Hulbert Obs. ($1.20 \div 2.55 \mu\text{m}$) and the atlas of Liège ($2.8 \div 23.7 \mu\text{m}$).

In the UV, the transmission of the atmosphere stops near 2800 Å. The farther UV has been photographed from rockets (Fig. 11). Near 1680 Å the character of the spectrum changes: the continuum disappears and the emission lines are observed. This part of the spectrum is emitted by the layers above the photosphere proper.

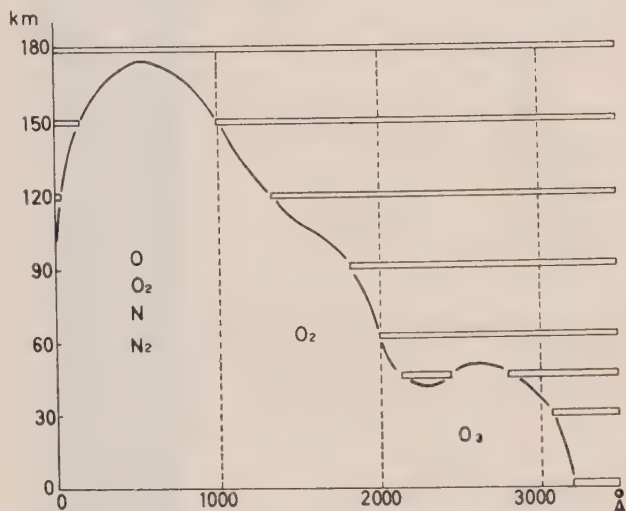


Fig. 10. — Transmission of the terrestrial atmosphere. The horizontal strips represent the spectrum, recorded at different heights in the atmosphere. For each wavelength the rays are considered as «transmitted», if at least 30% of the incident intensity reaches the layer concerned. The most important absorbing gases are indicated.

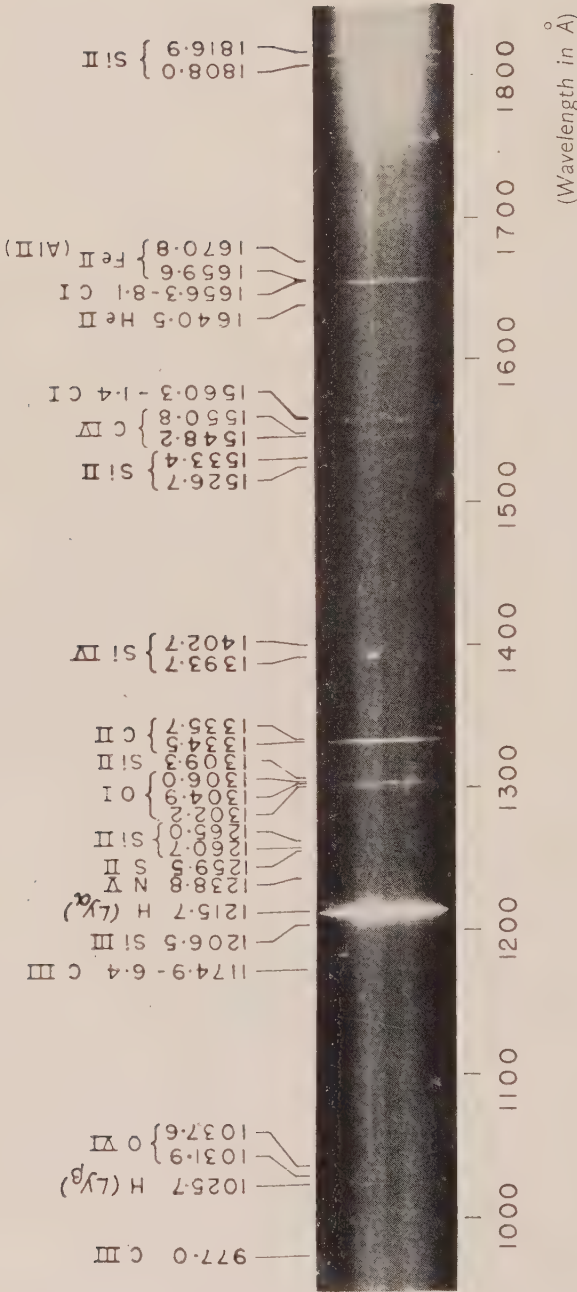


Fig. 11. - The far ultraviolet solar spectrum. Transition from the absorption towards the emission spectrum. (After JOHNSON, MALITSON, PURCELL, TOUSEY: *Astrophys. Journ.*, **127**, 80 (1959)).

The Fraunhofer spectrum shows more than 20 000 lines of neutral atoms, singly ionized atoms and a few molecules; 60 elements have been identified. Hydrogen and helium are practically all neutral; most of the metals, however, are for a great part ionized. In deeper layers the ionization of hydrogen begins, because of the increasing temperature; in higher layers (chromosphere and corona) the ionization also increases, as well because of the low pressure as of the again increasing temperature. The photosphere, therefore, is about the coldest solar layer and a region of minimum ionization. The importance of a Fraunhofer line is characterized by its *equivalent width*, which is a measure for the total energy which has disappeared in the line. From the equivalent widths, the abundances of the elements in the solar gas may be derived; an extensive program on this subject has been undertaken by the Michigan and the McMath Hulbert observatories. We give a little table where $\log N$ is listed for some important elements.

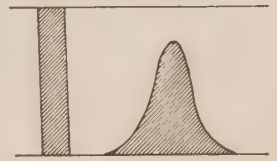


Fig. 12. - Equivalent width of an absorption line.

H	12	N	8.15
He	11.3	O	8.68
Li	0.83	Na	6.14
Be	2.43	Mg	7.27
C	8.28	Fe	6.83

The predominating elements are hydrogen and helium, which have an overwhelming abundance.

Because He lines do not occur in the Fraunhofer spectrum, the important ratio He:H remains uncertain and has to be derived from the spectrum of prominences.

If we except the lightest gases, the relative abundances of the elements in the sun are almost the same as in the other stars and on earth. Recently, however, some striking differences have drawn the attention; they become very important in view of the theories on element formation in the interior of the stars. We mention the following discrepancies:

Th/Pb is about 100 times smaller on the sun than on earth;

D/H is $< 4 \cdot 10^{-5}$ on the sun; on earth: $1.5 \cdot 10^{-4}$.

$^{12}\text{C}/^{13}\text{C}$ is 10^4 on the sun; on earth: 90.

2.1. *Model of the photosphere.* - Thus we call a list of the principal properties of the photospheric gases as a function of the depth x ; more especially T , P , P_{at} , κ , τ . From theory it is seen, that the optical depth $\tau = \int \kappa dx$ is a

more convenient co-ordinate; however it is very useful to convert eventually all data to the *geometrical depth* x , which alone gives a true picture of the space relations.

Model of the photosphere (partly after G. ELSTE).

τ	x	T	$\log P$ (dyne/cm ²)	$\log P_{el}$ (dyne/cm ²)
0.01	— 50 km	4 625	3.9	— 0.047
0.1	+ 200	5 090	4.6	+ 0.83
1	+ 335	6 460	5.1	+ 1.84
7	+ 450	8 260	5.4	+ 3.30

From the chemical composition we first compute the ionization and the excitation of the gases for each combination of T and P_{el} . Then we calculate for each combination the absorption coefficient κ , which is mainly due to the negative ion H^- , but for a small part also to the continua of neutral H , and (in the UV) to the continua of metals and the molecules CO , NO , N_2 .

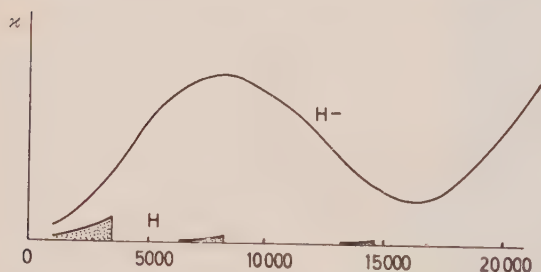


Fig. 13. The absorption coefficient in the photospheric layers. Contribution of H^- and of H .

These data being prepared, we calculate the temperature as a function of the optical depth, making use of the concept of *radiative equilibrium*.

Finally we calculate the pressure at each layer, starting from the assumption of *hydrostatic equilibrium*.

In this way a model is found on which the table here above gives a few representative data.

This model explains quantitatively the energy-wavelength curve and the limb darkening. It explains more or less the line profiles and their center-limb variation, though a precise representation, applying to different types of Fraunhofer lines, has not yet been found. The remaining imperfections are due to two causes:

1) The population of the several ionized and excited atomic states does not entirely correspond to local thermodynamic equilibrium but is partly determined by radiation; in the formation of strong lines, especially in the central parts, there is a chromospheric contribution.

2) Our models describe only the *mean* properties of each layer; however, we have to take into account the inhomogeneity, due to the granulation.

A good start has been made towards the calculation of more detailed and precise models.

2.2. Atomic processes determining the line profiles. – The formation of a Fraunhofer line is always due to energy transfer from that wavelength towards the other parts of the continuum. The absorption of energy is determined by the population of the lower level, the emission is determined by the population of the higher level.

The width of a Fraunhofer line is determined by:

- 1) thermal motion;
- 2) turbulence, either microturbulence or macroturbulence; a good theory, including both, has not yet been given;
- 3) radiation damping;
- 4) phase disturbances by H atoms and by electrons;
- 5) hyperfine structure, mainly due to the isotopes.

Special difficulties are met with in the theory of the hydrogen lines, which are broadened by the statistical fluctuations of the field, resulting from the combined action of the charged particles. At first theoreticians concluded, that only the action of ions had to be taken into account; an improved theory of Kolb includes also the electrons, but is only partly confirmed by the laboratory experiments. In the case of H_α , the special resonance forces of hydrogen atoms on each other seem to play a role.

3. – The outer layers of the sun: the chromosphere.

3.1. The stratified structure of the chromosphere as a function of height. – The chromosphere is a very thin layer, directly overlying the photosphere. It may be studied especially during total solar eclipses; when the moon has covered the entire photosphere, there remains during a few seconds an almost linear luminous arc, emitting bright monochromatic lines (flash spectrum).

During these few seconds it is possible to study the detailed structure of this thin layer as a function of height. While the moon is gradually covering the chromosphere, we measure the radiation emitted by a segment of a monochromatic flash arc, and we follow how this radiation decreases with time. By differentiating, we determine the contribution of each *surface* element of the projected chromospheric image; and from this again we derive the emission of each *volume* element, taking into account the self-absorption. In this way, for most metals scale-heights of (200 : 600) km are found.

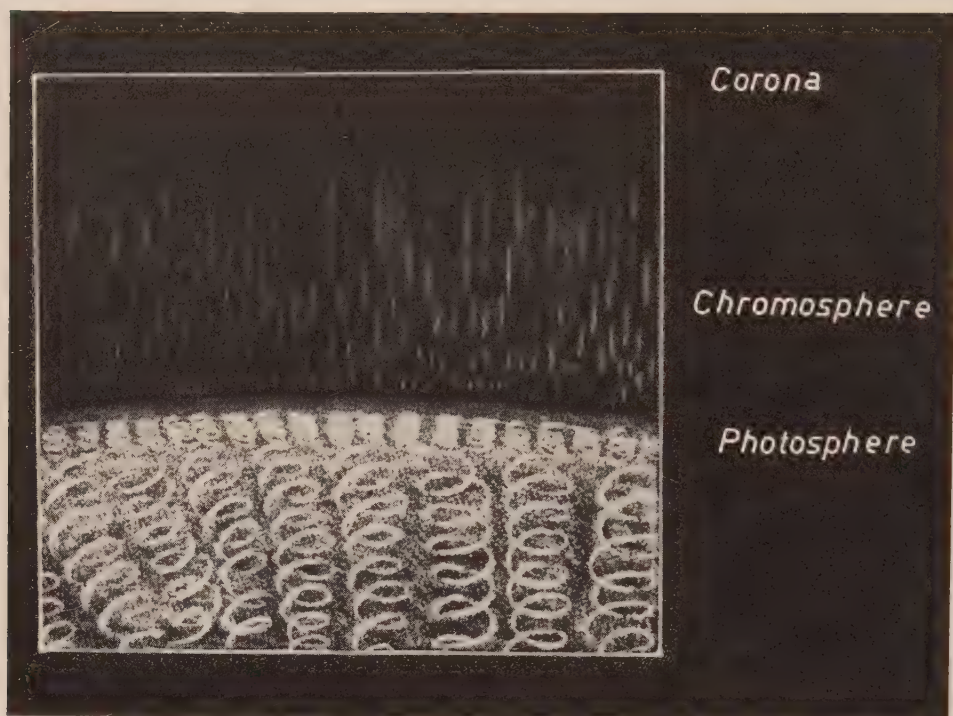


Fig. 14. — The outer layers of the sun.

With respect to the Fraunhofer spectrum, the line spectrum of the chromosphere shows many striking differences, pointing to a high ionization: the chromosphere is a good conductor. In quantitative calculations it is not al-

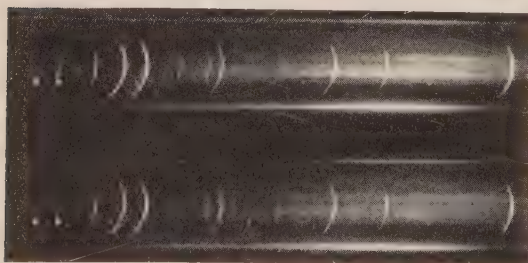


Fig. 15. — Flash spectrum of the chromosphere, obtained by J. HOUTGAST at the 1952 eclipse.

lowed to assume local thermodynamic equilibrium; for each volume element, the population of the atomic levels has to be calculated in steps: *a*) a population of the levels is assumed in zero approximation; *b*) we calculate the radiation field, due to the photospheric, chromospheric and coronal emission reaching the volume element which we are studying; *c*) we equate the emis-

sions to the absorptions, taking also into account the collisions, and find more precise values for the population; *d*) the calculation is repeated with better values for the chromospheric radiation, etc. This program has not been completely worked out yet.

3.2. The spicular structure of the chromosphere.

a) Another complication arises, because the high chromosphere appears to have a spicular composition. This is clearly seen on direct photographs during eclipses, obtained in excellent conditions of seeing. It may be studied even better outside eclipses with monochromatic filters: in H_α for example we observe a feebly luminous layer, 5000 km thick, striated more or less perpendicularly to the limb, and numerous individual *spicules*, growing above the general level up to 10000 or 20000 km, and disappearing in the course of

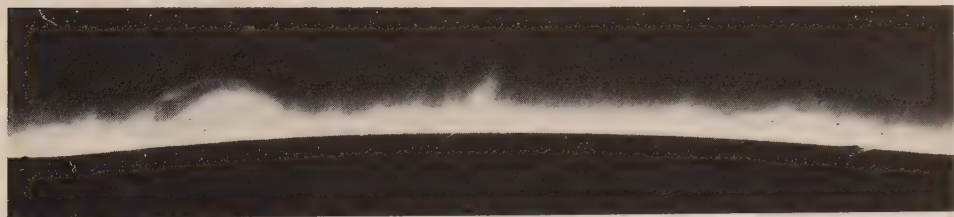


Fig. 16. — The chromospheric spicules. Photographed by R. B. DUNN, Sacramento Peak Observatory, in H_α light.

some minutes. Each spicule has a thickness of about 500 km. At many places along the limb, they show an inclination, which may correspond to the direction of the local magnetic field. From their spectrum these spicules appear to have temperatures of $10\,000^\circ : 20\,000^\circ$, which means that they are relatively cold elements, imbedded into a corona of $500\,000^\circ$ or higher.

b) An analysis of the spectrum of the lower chromosphere shows, that also at this level hot and cold elements must be juxtaposed. The first are responsible for the emission of the hydrogen lines ($T=10\,000^\circ$); the last ones are emitting the metal lines ($T=4\,000^\circ$).

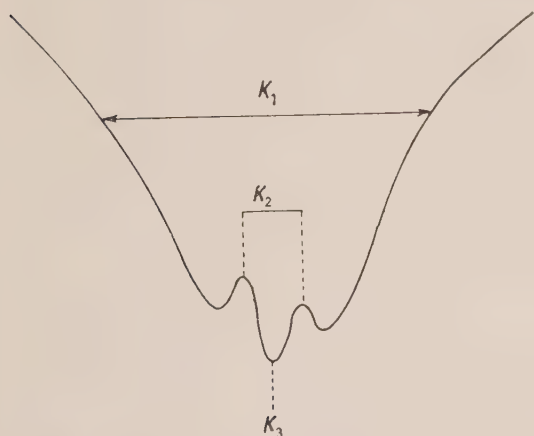


Fig. 17. The profile of the Ca^+ line K.

From these different sources of information the temperature distribution may be derived. It is not yet ascertained, how the curves have to be connected in the region of the intermediate heights and whether in the lower levels the term «spicules» should apply either to the cold or the hot elements.

From this model we may

compute the radio-radiation, to be expected at wavelengths below 3 cm, originating mainly in the chromospheric region. A satisfactory agreement is found.

3'3. The chromosphere against the disc. Spectroheliograms. — Two instruments mainly are used for the regular observation of the chromosphere, with its flares, prominences, plages:

1) The monochromatic filter, introduced by LYOT: plates of quartz and calcite between sheets of polaroid give cannulated spectra, in such a way, that only a band around H_{γ} is transmitted, with a halfwidth of $0.7 \text{ \AA}$. With this instrument, beautiful cinematographic records of disturbed regions have been obtained, which are demonstrated with a time-scale, compressed by a factor between 100 and 500.

2) The spectroheliograph, acting as a monochromator, and making photographs in almost monochromatic light (bandwidth of the order of $0.1 \text{ \AA}$). The nearer the selecting slit approaches the center of the line, the stronger are the absorption and scattering of the light and the higher is the effective level of the spectroheliogram. The components of the Ca^+ resonance line, called K_1 , K_2 , K_3 correspond with heights of 600, 2000 and 4000 km: the components $H_{\alpha 1}$, $H_{\alpha 2}$, $H_{\alpha 3}$ correspond with 3500, 4500 and 5000 km.

The undisturbed chromosphere shows:

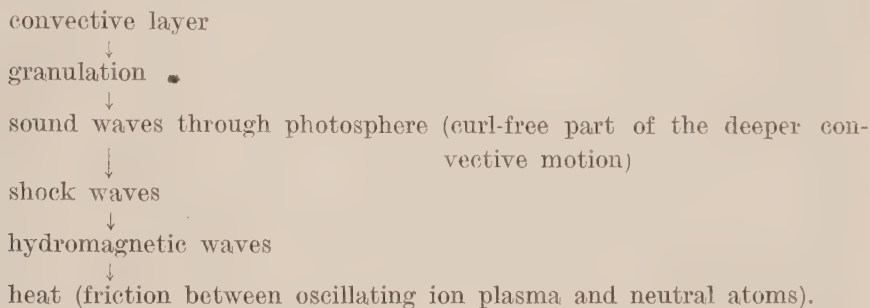
- fine mottles (perhaps the spicules, seen end-on);
- coarse mottles;
- a coarse network.

The distinction between such details and the background may be due to slight differences of temperature, differences in microturbulence (symmetric), or macroturbulent line shifts (asymmetric). Regions where there is a magnetic field may be heated more. In certain temperature intervals, an increase of temperature will decrease the amount of Ca^+ (by double ionization) but increase the amount of excited hydrogen (which is not yet ionized). This explains, why the mottles may be dark in Ca^+ light, bright in H_{γ} . The striking difference between the mottled structure of Ca^+ spectroheliograms and the fibrous structure of H_{γ} records might be understood, if we assume that the first ones show *temperature* differences and the second ones *density* differences.

3'4. Formation and support of the chromosphere. — The formation of the chromosphere is essentially due to the disappearance of the continuous absorption coefficient in the outer stellar layers, where the pressure of hydrogen and of the electrons decreases quickly and where consequently H^- dissociates. The thickness of the transition layer between photosphere and chromosphere may be theoretically calculated and is in fair agreement with the observations, if the proper amount of helium and the proper turbulence are assumed.

3'5. *The support of the chromosphere.* — The scale-height of the chromosphere is much greater than would correspond to the temperature of the spectrum. From the observed gradients it may be concluded that the chromosphere is mainly supported by turbulent motions, increasing with height from 3 to 15 km/s (at 3 000 km). Similar turbulent velocities are derived from the line-widths.

This turbulence has its origin in the convective layer:



The temperature distribution in the chromosphere is determined by the condition, that the gain of heat is compensated by the radiation and downward conduction. In principle this determines also the height where the corona appears and the heating of the corona itself.

3'6. *The transition between the chromosphere and the corona.* — The far-ultra-violet solar spectrum beyond 1680 Å takes the character of an emission spectrum. Indeed, for the radiation inside a spectral line the absorption coefficient is higher than for the neighbouring continuum; consequently the line originates at higher levels than the background. And since in the chromosphere the temperature increases with height, the lines are bound to become emission lines. Lines of He, C, O, N, Al, Si, Fe in different stages of ionization are observed. The Ly_{α} line at 1210 Å, very strong, but only about 0.5 Å wide, is a striking feature. The equilibrium of the ions is determined by the condition, that the collisional ionization is balanced by the recombination; temperatures of $10\,000^{\circ} \div 200\,000^{\circ}$ appear to exist in this transition region between chromosphere and corona.

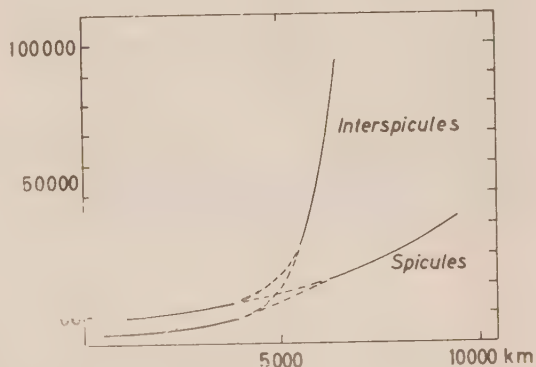


Fig. 18. Hot and cold elements in the chromosphere.

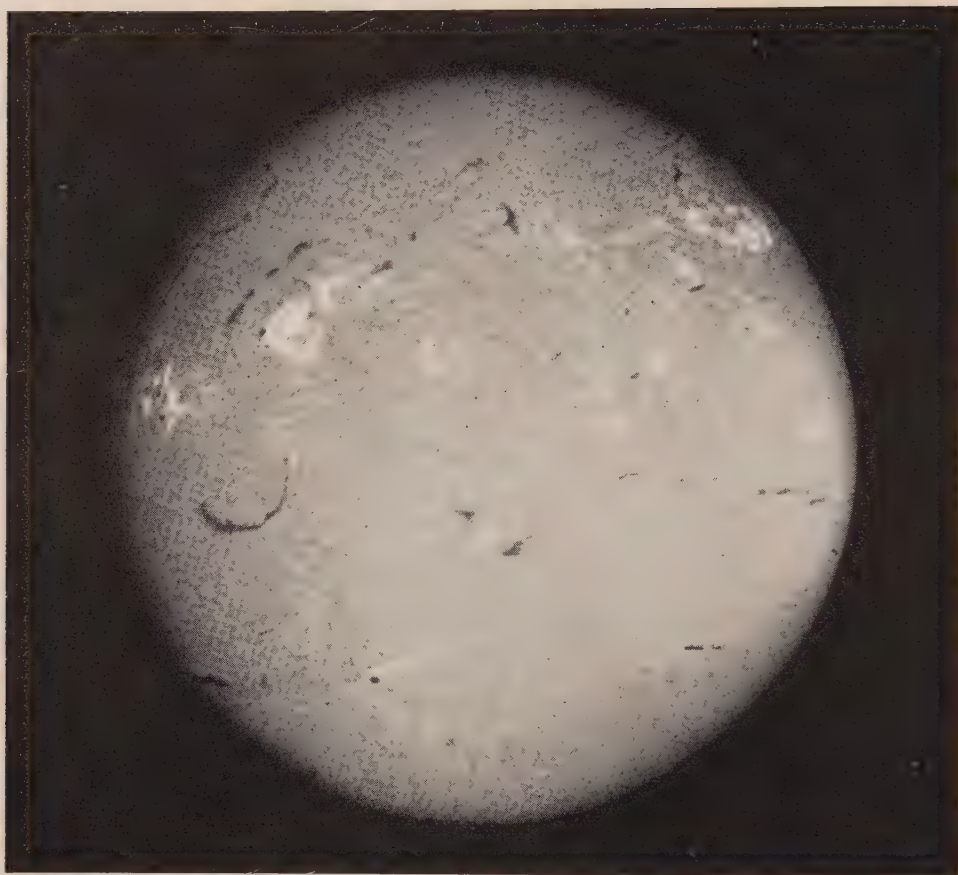


Fig. 19. — Spectroheliogram in H_{α} , with mottles, filaments and chromospheric faculae.
Photographed by J. DAMEN STERCK, Utrecht, 28-II-1959.

4. — The corona.

The corona is so faint, compared to the brightness of the sky and the stray light in a telescope, that it can only be studied well during total eclipses. In mountain stations, the coronagraph permits the observation of the brightest monochromatic features, close to the limb and (in the best circumstances) up to $0.4 R$. By photoelectric recording, it is possible to observe also some features of «the white corona». The corona rotates together with the main body of the sun: structures observed at the E limb are often recognized 14 days later at the W limb. By interpolation the structure of the corona over the whole visible hemisphere may be followed day by day. Daily maps of the corona are published by the mountain observatories.



Fig. 20a. — The solar corona at a minimum of solar activity; photographed by WALLENQUIST (1954).

The forms of the corona are a function of the 11-year cycle. Typical features are the *streamers* and the *polar bushels*; the last ones are characteristic for the minimum phase; they follow the magnetic lines of force.

Motions in the corona are seldom and occur in localized parts only. The films, made by DUNN, often convey the impression of stationary structures, of which the excitation varies.

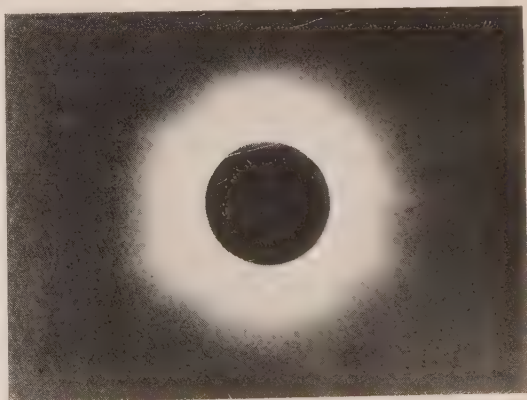


Fig. 20b. — The solar corona at a maximum of solar activity. Photographed by the Naval Observatory (1905).

4'1. *Spectral composition.* — The spectrum is the superposition of three components:

1) Solar light, diffused by the electron cloud around the sun; the Fraunhofer lines are blurred by the Doppler motions (K-corona). This fraction is polarized.

2) Solar light, diffused by dust in interplanetary space; a space around the sun is empty, but the cloud between the sun and the earth is seen projected upon the corona (F-corona). This fraction is probably unpolarized.

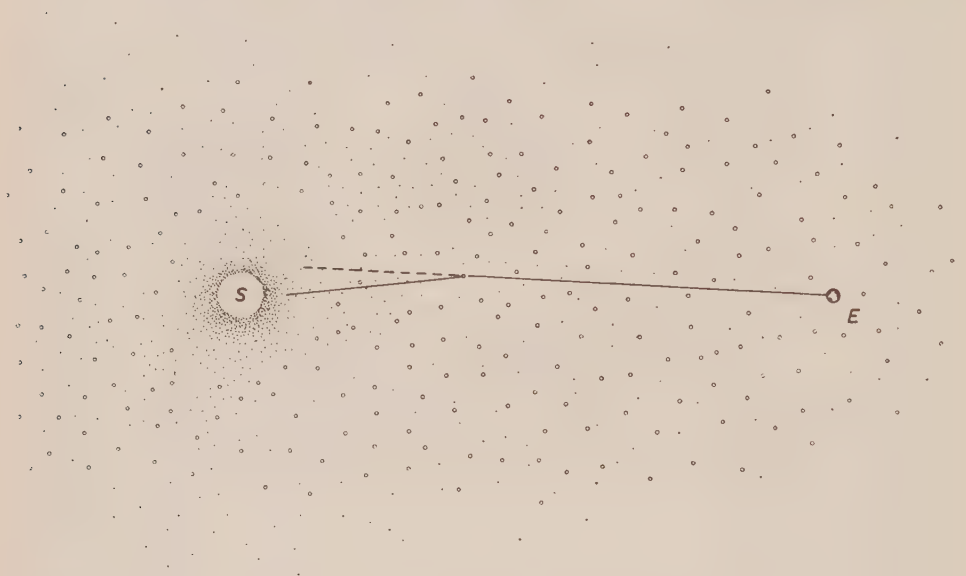


Fig. 21. — The formation of the F corona.

3) Monochromatic emissions by Ca, Fe, Ni, A in different degrees of high ionization. These lines are already observed at heights below 10 000 km.

The ionization is due to collisions, and is counterbalanced by photorecombinations. The excitation is due: near the sun, to collisions, and at greater distances to absorption; in general only the first level over the ground state is excited. From a comparison between ($\lambda = 6374$ and 5303) the red and the green line of Fe X and Fe XIV, the detailed temperature distribution may be derived; in general temperatures near 2 400 000 K are found. In active regions where the yellow line of Ca XV at $2\,5696$ appears, the temperature may reach $6 \cdot 10^6$ degrees; the hottest regions are characterized by the fainter yellow line at $2\,5445$ (also Ca XV?).

It is possible to disentangle both components: *a*) by studying the depth of the Fraunhofer lines; *b*) by measuring the polarization. If this is correctly done, the two results agree; this justifies the assumption, that the F-corona is practically unpolarized. The cloud of ionized gas and dust around the sun merges gradually into the gas and dust of interplanetary space, which has been studied recently by observations of the zodiacal light.

The *temperature* of the corona may be determined by many methods. From line widths temperatures of $2.4 \cdot 10^6$ are derived, which (according to the latest results) agree with those from the ionization and from the radio noise. In *coronal condensations* the temperature reaches $6 \cdot 10^6$ and the density may be higher by factors of 10 or 20.

The *far UV spectrum* may be calculated theoretically for an isothermal corona. The quiet corona should radiate down to $20 \text{ \AA}$, which is confirmed by rocket measurements. During flares, radiation down to $1.5 \text{ \AA}$ has been observed: this can only be understood if the temperatures in the active regions are so high, that the *K-envelope* of the Fe atom is excited ($T = 10^7 \text{ }^\circ\text{K}$).

The *radio-radiation* gives a wealth of information about the corona and all its perturbations. The radiation of the quiet sun is due to free-free transitions of the electrons in the field of the ions; the shortest wavelengths originate in the chromosphere, longer wavelengths correspond to increasing heights. From the radiospectrum, a model of the transition region between the chromosphere and the corona is found (PIDDINGTON):

$h = 3000$	5000	10000	15000 km
$T = 5200$	6250	33000	555000 $^\circ\text{K}$.

The *outer corona* has been observed at great distances from the sun, by studying the occultation of the Taurus radiosource. Every year the sun passes near this radio source. Already at distances of 10 or $20 R_\odot$, the radiosource

Densities in chromosphere and corona.

(Numbers adapted from DE JAGER: *Handb. Astrophys.*, III).

Height (km)	$\log N$ cold	$\log N_e$ cold	$\log N_e$ hot	
0	15.6			
1000	13.5	11.3		
2000	12.8	10.8		11.3
3000	12.3	10.5		10.9
6000	9.4	9.4		10.9
15000 = $1.022 R_\odot$		(8.5)	8.2	8.7
1.1		—	7.8	8.4
1.4	—	—	6.8	7.6
2	—	—	5.8	6.6
3	—	—	4.9	5.4
5		—	4.1	4.4
			min.	max.

becomes weakened and elongated; apparently the rays of light are deviated by the density gradients in the fibrillar streamers of the corona. It does not look probable that the corona extends further than $30 R_{\odot}$, since there the centrifugal force of the rotation would already equal the force of gravity.

II. — Local Disturbances of the Solar Surfaces.

The sun shows rarely the full visible hemisphere in an entirely uniform condition, corresponding to the description given. Some periods of the year 1954 gave perhaps the best approximation of a *quiet sun*. Nearly always the photospheric surface is beset by local perturbations of many different kinds (spots, flares, prominences, faculae, coronal streamers), which exhibit most interesting reciprocal relations and are often the source of characteristic radiation and geophysical effects. They are grouped together in so-called *centers of activity*.

For this reason, solar observatories around the whole world keep the sun under continual watch. By co-operative effort, perturbed areas are indicated on daily solar maps, published by the observatories of Meudon-Pic du Midi, Freiburg (Capri), Climax, Mitaka (Tokio), and by the Soviet observatories (Solnečnyj Dannyj). The Royal Netherlands Meteorological Institute of de Bilt and the Russian Institute for Terrestrial Magnetism, etc., publish lists of daily solar observations, combined with geophysical data. Important warnings are given by a system of radio-*ursigrams*. «Synoptic» maps, summarizing the whole of solar activity during a 27 days rotation, are published by Zürich, Uccle, Mitaka. A *Quarterly Bulletin of Solar Activity*, edited by Zürich on behalf of the International Astronomical Union gives an excellent general survey, but is published with a great delay; the same applies to the Soviet Catalogue of Solar Activity.

1. — Sunspots.

Among all perturbations of the solar surface, sunspots were the first to be noticed; even now they are the easiest observable index for a solar perturbation. They appear mostly in pairs (general direction EW), often surrounded by smaller spots. They rarely are seen outside the latitude belts $0^{\circ} \div 45^{\circ}$.

Large spots present an *umbra*, in which recently granules have been discovered: the umbra is surrounded by a *penumbra*, showing radial structure; outside the penumbra a broad bright ring is discernible.

The spectrum of the umbra corresponds to an excitation temperature of

4000°. In comparison with the photosphere the density is reduced, the gases are slightly less transparent. The Fraunhofer lines are slightly broadened by a « turbulence » of $(2 \div 3)$ km/s, to be interpreted probably as local differences in the vertical component of the motions. Due to the lower temperature, the spectra of molecules are much more developed. It remains unsatisfactory, that the model of the umbra and the model of the photosphere cannot yet be adjusted in height relatively to each other.

In the umbra the Fraunhofer lines show beautifully the Zeeman effect, corresponding to fields up to 4000 oersted. In almost every sunspot group a bipolar field distribution is observed, the leading spot and the following spot having opposite signs. The polarities are interchanged on the other hemisphere and in the next cycle. Above the umbra the field is almost perpendicular to the surface; farther away from the center of the umbra the lines of force are more and more inclined and at the outer boundary of the penumbra almost horizontal. The magnetic field persists throughout the life of the spot, though the area of the spot decreases more and more.

From Doppler effects in the penumbra, it follows that the gases in photospheric levels are

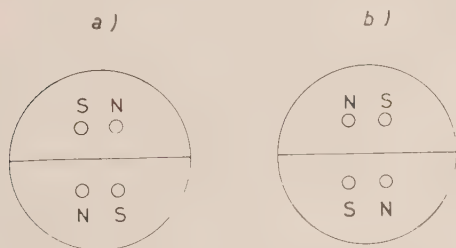


Fig. 23. - Magnetic polarity of sunspots.
a) even cycle; b) uneven cycle.

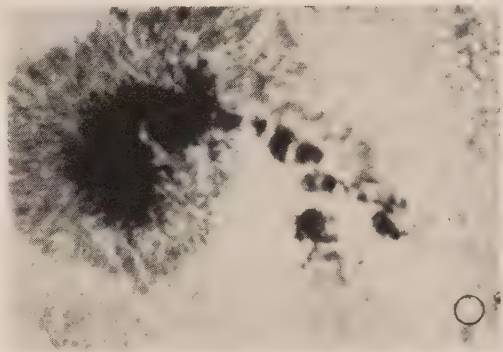


Fig. 22. - A big sunspot. (RÖSCHE: *L'Astronomie*, 71, 141 (1957)).

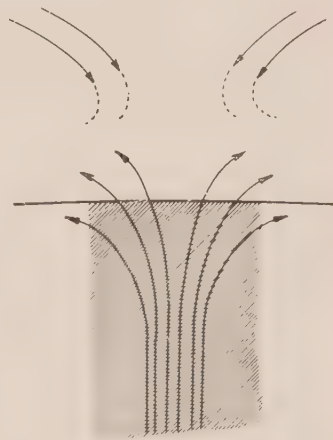


Fig. 24. - Gas currents in a sunspot.

streaming out in a broad and shallow sheet, while they are streaming in at chromospheric levels (e.g. 2000 km above the limb). In spectroheliograms, a spiral structure is sometimes observed over sunspots; this is due to Coriolis forces, on both hemispheres it corresponds to the inflow in a depression.

1'1. *Origin of sunspots.* — The most characteristic feature of a sunspot is the magnetic field. It is found to exist already before the apparition of the spot and to persist after its disparition.

Magnetic fields must automatically originate in a highly ionized gaseous medium. Because of accidental fluctuations in the electron concentration, weak electric and magnetic fields will originate. These are intensified by the « spaghetti process »: due to the great electric conductivity of the gas, the electrons and ions can only move parallel to the lines of force, which are « frozen into the gas ». Because of turbulent motions, these lines of force will stretch, while their cross-section decreases and more lines are pressed together. This process goes on, till there is equipartition between the magnetic and the kinetic energy, according to the equation

$$\frac{H^2}{8\pi} = \frac{1}{2} \rho v^2.$$

Apparently, by local violent convection some of these field lines are brought to the surface, forming a pair of spots. The magnetic field inhibits the vertical convection in the higher photospheric levels, the convection currents are deflected sideways, they fan out: the surface layers of the spot become less hot, while the region around is heated and shows the bright ring. It is not yet clear, why the limit of the umbra is so sharp.

1'2. *The sunspot cycle.* — The number of sunspots f and the number of spot groups g on the visible hemisphere are used as an index of solar activity according to the conventional expression for the *relative numbers*:

$$R = K(10g + f).$$

These relative numbers vary from 0 to about 300; they seem to show an

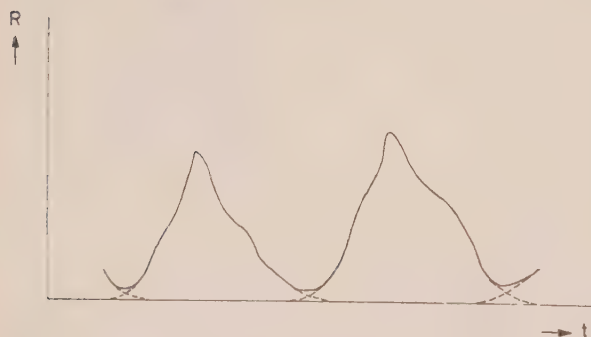


Fig. 25. The sunspot cycle and its analysis near the minima.

irregular cycle of 11.0 years (the duration of the individual cycles varies between 8 and 17 years). Actually, each « cycle » is to be considered as an activity eruption on itself; the so-called « minima » should be decomposed, each eruption starting from zero and finishing with zero. This becomes clear if we notice how the spots of a

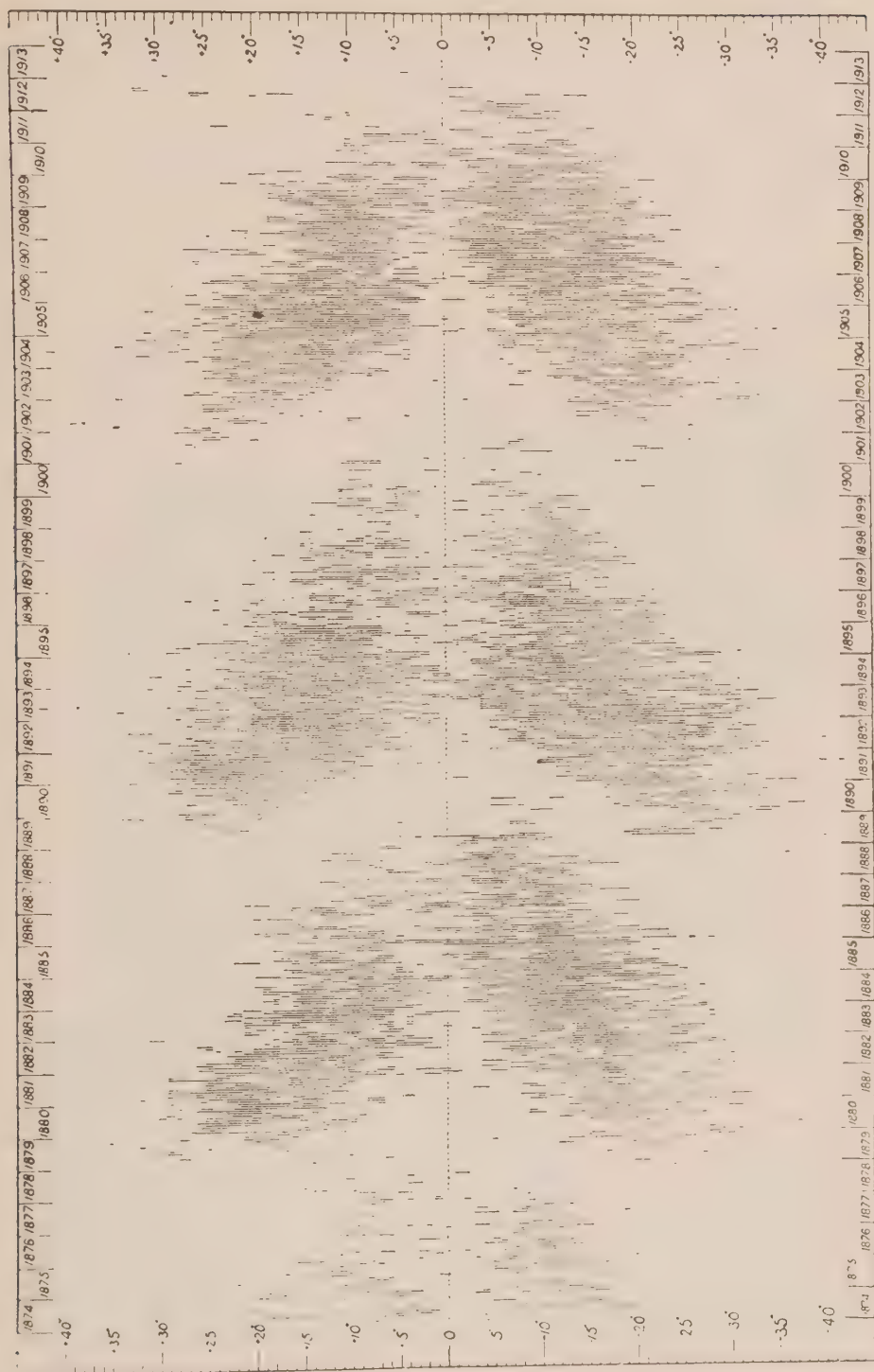


Fig. 26. — Distribution of the spots in heliographic latitude (« butterfly diagram »).

new cycle start at high latitudes and how they approach the equator at the end of the cycle (SPÖRER). The change of magnetic polarity suggests that two cycles belong together; it has been shown that each «even» cycle should be combined with the *following* «uneven» cycle to a 22 year-cycle.

A similar eleven-year cycle is found in most solar phenomena. The origin of this pseudo-periodicity is not yet clear; it must certainly be due to large scale currents in the convective layer.

2. – Faculae-plages.

2'1. *Photospheric faculae*. – A network of coarse mottles is observed here and there on the disc in white light around spots. It is visible only near the limb; this must mean, that the temperature of these objects is somewhat higher



Fig. 27. – Photospheric faculae. Photographed at the Potsdam Observatory by TEN BRUGGENCATE: *Zeits. Astrophys.*, **19**, 2 (1939).

in the upper layers, and somewhat lower in the deeper layers, compared to the undisturbed photosphere.

2'2. *Chromospheric faculae*. – They are found on spectroheliograms, above the photospheric faculae. Their life-time is considerably greater (250 days); they may be recorded as bright or as dark objects, depending on the line selected (Fig. 19).

They often correspond with magnetic fields, in general bipolar (BM) as the spots, rarely unipolar (UM) or polypolar (PM). Above UM regions the green corona line is stronger; they are the origin of recurrent magnetic disturbances on earth, which show the 27-day periodicity. The corpuscular beam, which they are supposed to emit, propagates with a velocity of about 500 km/s.

3. — Prominences and filaments.

3.1. *Quiescent prominences.* — They are observed beyond the limb of the sun as bright arches, thin as a leaf, resting on a few «pillars», and appear as dark *filaments* against the background of the solar disk. Typical dimensions: $200\,000\text{ km} \times 50\,000\text{ km} \times 10\,000\text{ km}$. They occur often at the W-side of an active region and are sloping slightly away from it (mean inclination: 8°). In general the filament is first oriented along a meridian, then it gradually changes its direction because of the differential solar rotation, and eventually it is almost directed along a parallel. At the same time it grows at its high latitude end and desintegrates at its low latitude end («poleward migration»).

These objects apparently are supported by magnetic fields. When a conducting cloud falls in such a field, Foucault currents are set up by which the motion is practically stopped. The support is only stable at these points where

the magnetic field is horizontal; in this way the thin leaflike form becomes understandable.

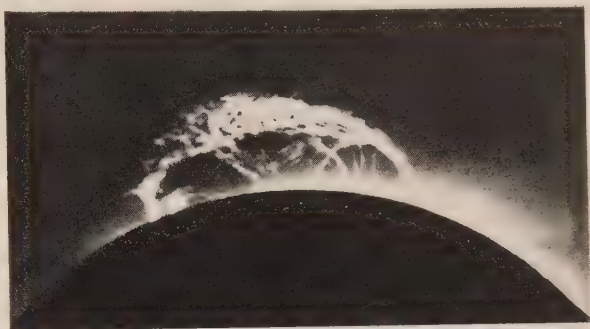


Fig. 28. — Quiescent prominence, photographed by A. S. EDDINGTON at the eclipse of 1919.

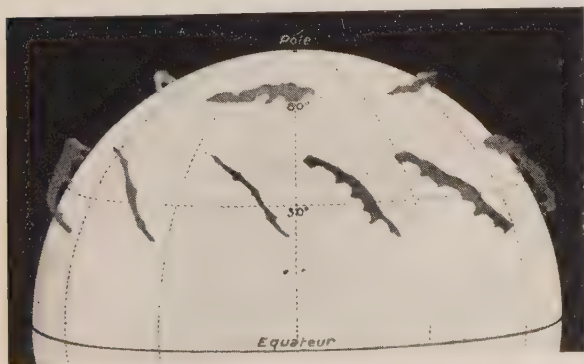
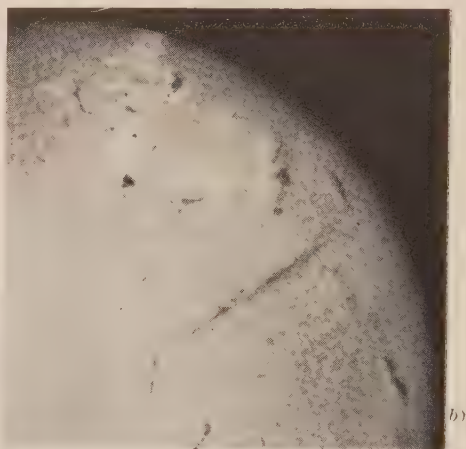


Fig. 29. — Schematic view of a quiescent prominence, displaced by the solar rotation. (RUDAUX and DE VAUCOULEURS: *L'Astronomie*, p. 271 (after L. and M.D'AZAMBUJA)).

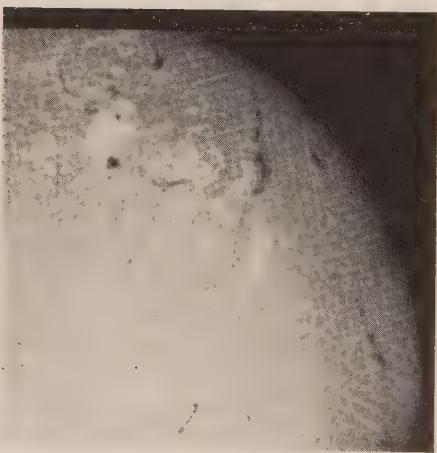
3'2. *Active prominences.* — Activation may be due to flares or to the formation of a new center of activity. Apparently the existing equilibrium is perturbed: the prominence streams off along the lines of force towards neigh-



a)



b)



c)

Fig. 30. — Sudden disappearance of a big filament on August 9, 1956, after records of Mrs. MARTRES (Meudon).

a) 12^h.45; b) 13^h.35; c) 14^h.45.

bouring spots or it is blown upwards by the magnetic detension (catapult mechanism), showing often sudden accelerations. In $\frac{2}{3}$ of the cases, the prominence reappears in the initial position: apparently the main magnetic field is still present.

3'3. *Sunspot prominences.* — The special forms (loops, knots) observed near spots, are often connected with coronal condensations or with motions in the corona.

3'4. *Spectrum of prominences.* — At eclipses the spectrum of prominences shows almost all chromospheric lines.

From the brightness in H_α follows:

$T_{\text{exc}} = 3\,700^\circ$. This is probably also the electron temperature. The linewidths yield $T = 12\,000^\circ$, but this is apparently due to turbulent motion of (4 ± 8) km/s. For ionization potentials above 10 eV, especially for He and He⁺, the ionization equilibrium corresponds to temperatures which increase up to $20\,000^\circ$; this may be understood, assuming that the spectral radiation

below $1200 \text{ \AA}$ does not fall to zero but remains about constant at shorter wavelengths.

There is a faint continuum, probably due to scattering by the free electrons.

3.5. Formation of prominences. — A prominence is surrounded by the much hotter but much more rarefied corona. The product $P = NkT$ seems to be equal and this suggests that the prominence *condenses* out of the corona. This explains the phenomena of «coronal rain»: it also explains, that the corona is in general less dense around a prominence. Apparently an initial cooling is necessary, *e.g.* by a change in the magnetic field; if this cooling extends over a sufficiently big volume, through which the corona particles cannot penetrate and which emits radiation, the cooling will go on.

4. — Flares.

Flares are sudden brightenings of the facular field at the chromospheric level. Only in 17 cases they have been observed in white light; in monochromatic light (H_α) they are very frequently visible, often several times a day but it is not possible to predict where precisely they shall occur. Their intensity is estimated on a scale of 1, 2, 3, mainly according to their areal extension. Much more numerous are the *microflares*, whose diameters often do not exceed $1''$, though their brightness is comparable to that of a normal flare.

Flares originate near quickly developing spots; big flares show irregular forms, often corresponding to preexisting chromospheric structures. The observation of limb flares shows, that they reach only heights of (7000 – 16000) km.

Often an almost stationary flare is surmounted by an ascending *surge* or eruptive prominence. In other cases, however, the flare itself is moving upwards with a speed, reaching sometimes 100 km/s.

The life-time of a flare varies from a few minutes to a few hours. The brightness increase is always quicker than the decrease.

In the spectrum a number of bright emission lines are photographed, espe-

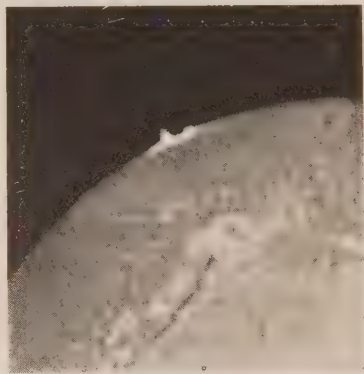


Fig. 31. Limb flare, observed at the Arcetri Observatory (Memorie No. 57, 1939).

cially of H, He, Ca, but also of other metal atoms and ions. There is mostly a very weak continuum, less than 1% of the background, sometimes weakly polarized (synchrotron radiation?). The H_{α} profile is partly or wholly filled up, in stronger flares the emission is much broadened. The central parts are chromospheric, their broadening is probably due to a combination of radiation damping and Stark effect ($T_{\text{exc}} = 7000^{\circ}$, $T_{\text{kin}} = 12000^{\circ}$). The wings of the line, studied with a high resolving power during the flash phase, are found to be composed out of characteristic *moustaches* which are the broadened emissions of grains, not greater than about $1''$, located at low levels, while their lifetimes are of the order of a few minutes only; this broadening is due to the Doppler effect of macroscopic motions.

The concomitant phenomena show, that the flare and the neighbouring disturbed objects emit different types of radiation and streams of corpuscular particles.

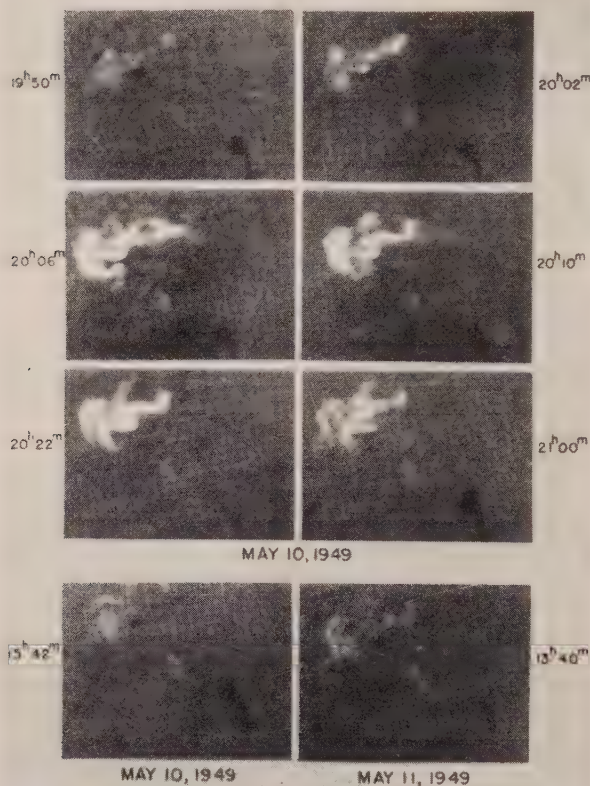


Fig. 32. — Development of a solar flare. (H. W. DODSON: *Astrophys. Journ.*, **110**, 385 (1949)).

1) Corona condensations above the flare
 emit soft X radiation $\lambda = (2 \div 6) \text{ \AA}$. Formation of a conducting layer in the terrestrial atmosphere, at about 65 km (normally 80 km); at this relatively small height, the ionized layers absorb the meter radiowaves and reflect the km waves. Dellinger effect, absorption of extraterrestrial radio noise, sudden enhancement of atmospherics, phase anomalies and field strength anomalies, crochets in geomagnetic records. Some of these effects start already a few minutes before the flare, they occur only on the sunlit hemisphere.

2) Corona condensations above very strong flares emit cosmic rays with relatively low energies, up to $11 \cdot 10^9$ eV, arriving $10^u \div 2^h$ after the flare; apparently they are diffused in interplanetary space, for the tail of the curve decays in the same way for all stations at the same latitude. They have practically the velocity of light.

3) Activation of distant filaments, perhaps due to the emission of Ly_α or to the effect of magnetic fields. Neighbouring filaments, which are not activated, could be colder and might contain more H_2 molecules.

4) 50 % of the flares are followed, within a few minutes, by a *surge*, ascending with a speed of several hundreds of km, and falling back along the same trajectory. Part of the matter is probably expelled.

5) Radiobursts are emitted by the successive coronal layers, through which the corpuscular beams are passing. Each layer emits its plasma frequency; by observing the gradual increase of wavelength, we are able to follow the ascending disturbance and to determine its speed. Two sharply distinct types of disturbance are observed (1000 km/s and 100 000 km/s); the high velocity disturbances originate in these bright flares, which showed a sudden expanse during the first stage of their existence (*flare-puff*).

6) When the corpuscular beams reach the earth, geophysical effects are observed: a) geomagnetic storms, 22 hours later for strong flares, 34 hours for small flares, 58 hours for flares with early outbursts (9100, 1200, 700 km/s); b) auroral phenomena, the hydrogen lines H_α and H_β showing pronounced Doppler shifts (400 and 3 000 km/s).

It is not entirely clear whether a stream of corpuscles keeps the same velocity all along its path from the sun to the earth, or whether there are

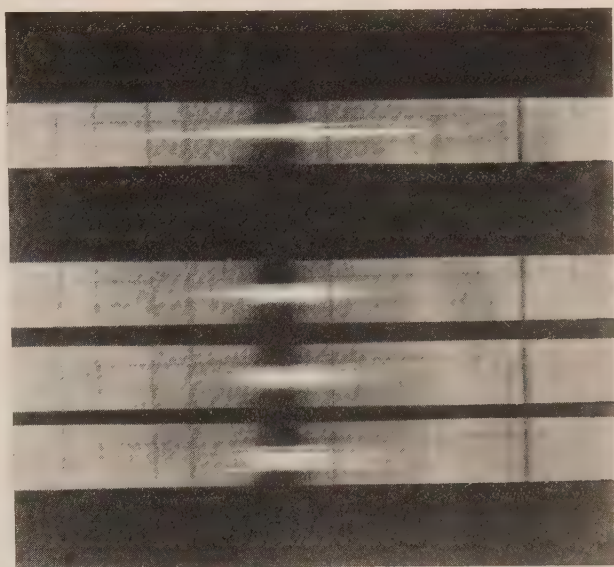


Fig. 33. - Spectrum of a flare near H_α , with characteristic moustaches. (Photographed at Utrecht by C. DE JAGER).

accelerating mechanisms in the corona or near the earth. For this reason it is often difficult to identify the corpuscles, producing a geophysical effect, and to reconcile their speed with the time interval between flare and effect.

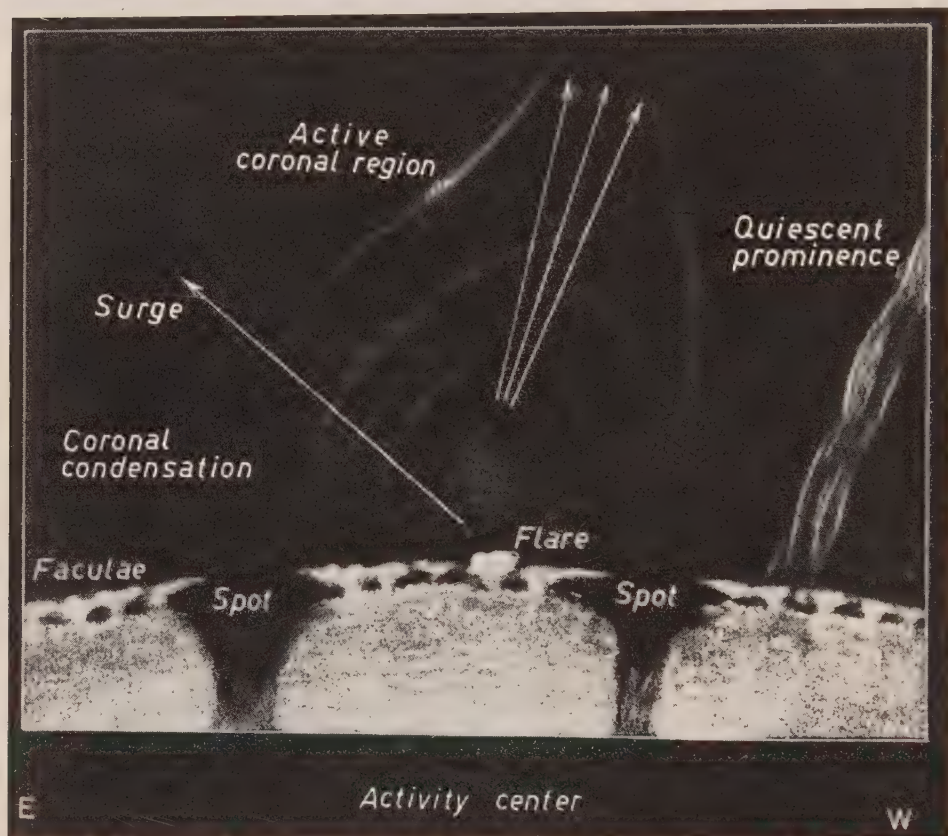


Fig. 34. - Schematic representation of a solar flare, with some concomitant phenomena.

The theory of these geophysical effects will have to be revised, taking account of the new discoveries concerning the zones of energetic particles (protons and electrons) at heights of 4000 km and 16000 km (above the earth). The outer zone seems due to solar particles, captured by the terrestrial magnetic field; the inner zone is populated by fragments of nuclei, formed by collisions of the primary cosmic radiation with atoms of the exosphere. The charged particles are spiraling along the lines of force of the terrestrial magnetic field, and are «reflected» near the poles, where the field-strength in-

creases. The aurora would be due to instabilities in the outer zone, triggered by solar effects.

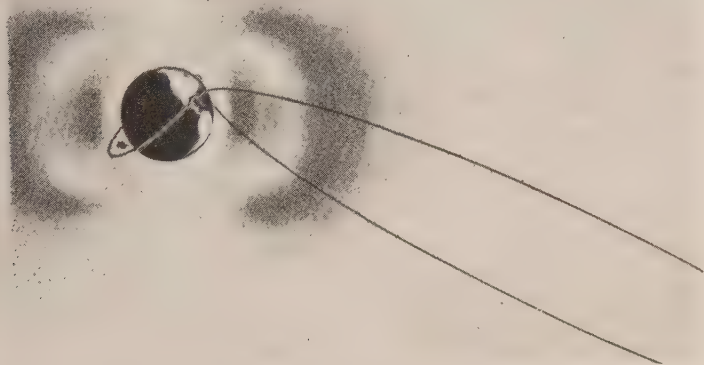


Fig. 35. - Zones of high-energetic corpuscular radiation near the earth. The orbit of an artificial satellite is also drawn. (*Scientific American*, March 1959).

4.1. *Theories about the origin of flares.* - Direct observation with the magnetograph shows, that flares originate between spots of opposite polarity, at points where $H = 0$ while dH/dx is high (this implies also that dH/dt is high). The fields of the two growing spots are assumed to move towards each other.

1) By induction strong potentials develop and between the magnetic fronts the electrons are accelerated and ejected; the higher their velocity, the smaller the effective cross-section of the ions for collisions and the longer the free path. This again increases the velocity and the heating.

2) Others believe that a «pinch effect» occurs: the different parts of the discharge, being parallel currents, attract each other and the plasma near the neutral point is compressed; since the magnetic field is frozen into the plasma, the total current remains constant but the current density increases.

On either side of the neutral point shock fronts develop, which are moving towards one another ($T = 0.3 \cdot 10^6$). During the collision of the two fronts, temperatures of $T = 10^7$ are reached. By bremsstrahlung X-radiation may originate, while perhaps neutrons and deuterium are formed. However, it should be kept in mind, that X-radiation is observed only when the flare raises high into the chromosphere or into the corona.

According to such a mechanism (or a similar one) the invisible «primary flare» in the lower corona emits an abundant stream of electrons or ions, part of which is shot down on the lower chromospheric layers, which are excited and flare up. This is «the visible flare».

5. - Conclusion.

It may be said, that it is now in broad lines understood how a mass of $2 \cdot 10^{33}$ g, composed of hydrogen, helium and a few metals, evolves to «the quiet sun» with its different layers and characteristic temperature and density distribution. However there are still considerable difficulties in the understanding of the perturbations, which are all connected to the enigmatic 11-year period. The combination of magnetic fields and hydrodynamic currents will explain the complicated phenomena of spots, prominences and flares; the radiowaves of the sun are giving most valuable and very detailed information on the outer parts of the sun, complementing what as been ascertained by optical methods.

APPENDIX

Recommendations to observers.

In the course of the lectures and of the discussion, several hints to solar observers emerged, which may be summarized as follows.

1) In ordinary circumstances, the relation between the burst and the coronal streamers is difficult to study, because the structure of the corona can only be observed near to the limb. However at the moment of a total eclipse more information becomes available. Radio-observers, therefore, should give special attention to burst phenomena during at least one week before and one week after the eclipse. This applies in particular to the next eclipse of October 2, 1959.

2) The relation between sudden disappearances of prominences (D.B.) and radio phenomena should be more carefully investigated.

3) It would be interesting to observe regularly the sun with a monochromatic filter in the light of the He line D_3 .

4) It remains an open question, whether bursts may occur without flares and without sudden ionospheric disturbances (SID). Statistical methods are perhaps less convincing than individual clear cases, in which we are sure that a good watch has been made and in which the source of the burst has been localized by interferometry.

5) The following proposal was made by Dr. DE JAGER.

Most European radio observers are obliged, by lack of instruments and personnel, to restrict their studies to only a few frequencies, to polarization or to interferometry. By co-operation between these observatories an interesting event could be studied much more completely. For this purpose the publication of numerical data is not sufficient, an intercomparison of the records themselves seems necessary. It is impossible to make multiple copies

of all these curves, but this could be done for the moments when interesting events occurred.

The proposal would be, to communicate weekly to a European Center the days and hours when observations have been made, the frequency on which they were obtained, and whether polarimetry, sweeps, or interferometry have been made. An observatory interested in a particular event could then readily obtain from the Center a list of the stations, where this event has been observed. Microfilms of the records and contact prints of the sweeps could be obtained. For practical reasons, this co-operation would be restricted to European observatories, the more because their longitudes are not too different (5° W to 45° E) and the chances for overlap greater. About 25 observatories would be involved.

It might be considered to issue now and then a simple, mimeographed publication, indicating the days and hours of routine observations for the different observatories, with the work they are carrying out. This would facilitate the interchange of data. Moreover it would then become apparent, in what frequency ranges important gaps occur, so that new instruments could be tuned to these bands. In this publication, interesting events might be pointed out.

The audience commented and approved this proposal. It was decided to ask for the co-operation of the European radio-observatories. Professor RIGHINI suggested that the Netherlands NERA Observatory could perhaps act as the co-ordinating center. The commissions for radio-astronomy of the IAU and of the URSI shall be kept informed about the proposed co-operation.

P.S. - As a consequence of the last proposal, an *Information Bulletin of Solar Radio Observatories in Europe* is now published by the Section IRA of Netherlands PTT, The Hague.

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INTERVENTI E DISCUSSIONI

C. DE JAGER:

A possible way to explain a part of the observations related to the meridional motions in the sun, might be the following (see Fig. 36).

Consider a mass of gas in the convection zone, moving radially outwards from point 1 to point 2. Its centrifugal force, being F_1 in the point 1 remains unchanged and is still the same in the point 2. There the centrifugal force acting on the surroundings

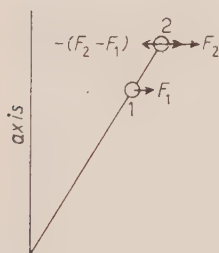


Fig. 36.

is $F_2 > F_1$. Hence there will be a net force $F_2 - F_1$ acting on the mass of gas, directed towards the axis. So the mass will not move radially but it undergoes a poleward force, which increases with increasing latitude.

If we now assume, as is often supposed, that sunspots are brought to the surface by a sort of large-scale convection, it is clear that they should move polewards, at least during the time in which this convection is still active.

We observe however that spots only move polewards at heliographic latitudes $> 16^\circ$. To explain this we turn to the equatorward motion shown by the butterfly diagrams: this shows that at the same time a constant equatorward motion occurs. It might be that the point $b=16^\circ$ is just the point when this equatorward motion is balanced by the poleward motion due to the convection motions.

— K. O. KIEPENHEUER:

I would like to make two remarks:

1) When speaking about the interpretation of spectroheliograms, you mentioned that the chromosphere is built up of «cold» elements imbedded in the corona, the spicules. It should be stressed however that these spicules occupy only a very small volume in the middle and upper chromosphere, probably less than 1% of the corresponding volume of this part of the corona.

2) As a probable cause of the visibility of chromospheric structures (spicules etc.) you mentioned turbulence and differences in temperature. I think, also the density is an important factor, the spicules certainly having more than ten times the density of the surrounding corona.

— K. O. KIEPENHEUER:

It should be pointed out, that the stretching of the lines of force alone will not help to increase the magnetic field. This will only enlarge the volume which is occupied by the field. In order to increase the field, the field lines have to be brought close together. Then more lines of force per unit cross-section will be available.

— J. KLECZEK:

I have computed the number of Ca XV ions as a function of electron temperature. As a result the maximum number of Ca XV ions occurs for a temperature of about 3 million degrees. That is in rather good agreement with the temperature determined spectroscopically from the yellow coronal line, if one takes into account the uncertainty of cross-section determination.

The Optical Phenomena Forming a Solar Center of Activity.

K. O. KIEPENHEUER

* *Fraunhofer Institute - Freiburg i.B.*

1. - Introduction.

Almost all variable phenomena on the sun can be considered according to D'AZAMBUJA as parts of a solar center of activity (C.A.), the optical phenomena as well as those in the radio frequency range. The number of the C.A.'s at a given time can be taken as a rough measure of solar activity. However the size of the C.A. can vary very much.

The difficulties which are encountered when a synoptical observation of a C.A. is wanted are considerable, not only because of the big number of the contributing phenomena, but also because their observation and measurement need very different instruments. A C.A. is a threedimensional phenomenon, which is extended over all the three layers of the solar atmosphere, which are accessible by optical procedures: The photosphere (mean density 10^{16} H atoms/cm³, temperature $\sim 5000^\circ$). It is the source of solar continuous radiation, the niveau of granulation, the layer in which the sunspots become visible. The chromosphere (mean density 10^{12} H atoms/cm³, temperature 5000° to 10000°) which can be observed only in monochromatic light, especially in the lines H_α and K , the structure of which differs strongly from that of the photosphere. The corona (mean density $10^7 \div 10^9$ protons and electrons/cm³, temperature $\sim 10^6$ degrees), which can be observed only at the sun's limb against the dark sky and only with the aid of special telescopes, the coronagraphs.

To judge and to overlook better the amount of information of optical observations, a short review will be given about observing techniques including the measurement of magnetic fields and about the limits of observation which are set by the terrestrial atmosphere and by the instruments. Then an inventory of all observable phenomena will be presented. With such prepa-

rations it will be possible to give a synoptical life story of a C.A. Finally it will be tried to work out a model which brings the large variety of phenomena into one simple physical picture. It will be shown, that the course of events in a C.A. and the nature of the single phenomenon can be described and understood best by the action of a magnetic disturbance which reaches the photosphere from the interior of the sun and which penetrates into the chromosphere and into the corona.

2. – The observation of the sun.

I do not want to give a compendium about the different methods of solar observation. It seems to me more appropriate to discuss here the degree of reliability and the completeness of the observations as well as their fundamental limits. As already said, very different types of instruments have to be used for the different layers of the solar atmosphere. Even the ideal meteorological conditions for observation are different for the different layers of the sun. While for the steadiness of the pictures of the solar surface a slight haze might be very good, for the observation of the solar corona a high transparency of the atmosphere and a perfect blue sky is wanted. Therefore it is not too astonishing that there is almost no observatory, which is equipped to observe all solar phenomena. In general a synopsis can be accomplished only by the close co-operation of a number of specialized observatories. An efficient co-ordination and the composition of coronal observations from one observatory and photospheric and chromospheric from another one meets considerable technical difficulties. Also the recording, the documentation and propagation of material is a difficult problem which has not yet been solved satisfactorily.

In the following some critical details of observing technique will be mentioned, for enabling you to judge better the quality of an observation and to see the possibilities of optical procedures:

Photosphere. – The best pictures are obtained with refractors in integrated light, prime aperture 10 to 20 cm, diameter of the sun's disk on the negative at least 10 cm. There is a great number of observatories, which obtain on 50 to 100 days/year during $\frac{1}{2}$ to 1 hour a resolution of 2" to 3" (1" = 750 km on the sun), on 10 to 20 days even 1" to 1".5. Nevertheless because of lack of international co-ordination no observation series are available, which give a 2" resolution for a period of some weeks. The cinematography of sections of the photosphere is being done, however the scientific evaluation of such films is very tiresome and has limited success because of scintillation which displaces and deforms the pictures, one against the other. The international

daily recording, counting and classification of sunspots works practically gapless. Details about the development of a spot group within 24 hours are available, however, only occasionally.

The method recently developed by SCHWARZSCHILD and others [1] to photograph the sun from an unmanned balloon at a height of 25 to 30 km looks very hopeful. The guiding and focusing of such an instrument can be done from the ground by using a television bridge. A resolution of $0''.3$ has been obtained, which corresponds to the theoretical resolving power of the parabolic mirror of 30 cm in diameter which was used.

Chromosphere and prominences. — The observation of the chromosphere has to be made in the light of a Fraunhofer line. Spectroheliograph and Lyot-interference filters are in use for this purpose, which give a passband of 0.2 to 1 Å. The amount of light available in such a narrow band being only $\sim 1/1000$ of that in integrated light, the exposure times are much longer and consequently the obtained resolution because of seeing much smaller. With a good spectroheliograph in permanent routine work a resolution of $3''$ to $4''$ is obtained, with interference filter (H_α) $2''$ to $3''$. Long series of filter-grams over hours and days give an average of only $4''$ to $5''$.

Also the day to day survey of the chromosphere and prominences is fairly complete, while detailed information about the variations from hour to hour or for every minute are only available for a small fraction of the time. This fraction was somewhat enlarged during the IGY. The visual survey of chromospheric flares with spectrohelioscopes and filters is very complete. Only few percent of the flares escape observation. Photographic and photometric material about the development of flares is still rare. The same is true with a few exceptions [2] for the photometry of other solar phenomena in the chromosphere, especially the faculae and their development.

A permanent quantitative record of the chromosphere (about every minute), which admits photometric and spectroscopic evaluation afterwards would mean a tremendous investment of equipment, film and personal. For this reason detailed recordings are concentrated in intervals of special interest. It follows from this that in many cases individual appointments between optical and radio astronomers cannot be avoided.

Corona. — The brightness of the solar corona is only 10^{-5} to 10^{-6} of that of the sun. Therefore the scattered light of our own atmosphere and of the instrument will affect seriously the observation of the corona, no matter whether visual, photographic or photoelectric procedures are applied. There are about 7 coronagraphs on our planet working on a routine base. Together they give an almost gapless day to day record of the variations of coronal brightness along the sun's limb, especially in $\lambda 5303$ and 6374 , sometimes also in other lines or in integrated light.

The coronal brightness at greater distances from the solar limb and the coronal survey in integrated light are not yet objects of a regular routine program. The data obtained with the different coronagraphs are mostly based on visual and photographic methods and can deviate from each other considerably. More reliable photoelectric procedures have been developed but have not yet come into regular use.

The radio astronomer is specially interested in the middle and outer corona (correspondingly plasma frequencies 1000 to 100 MHz). These layers unfortunately can be observed only rarely and then only when they just pass the sun's limb. The photographic recording of rapid variations in the corona, *e.g.* in connection with flares or during the occurrence of type III bursts meets serious difficulties because of the exposure time of 1 min, which corresponds for a coronal velocity of 600 km/s already to an uncertainty of 36 000 km.

Magnetic fields. – The visual and photographic measurement of the magnetic field in the umbrae of sunspots down to about 100 to 200 gauss does not offer any technical difficulties. Nevertheless the observing material available (mostly Mt. Wilson, Potsdam and Crimean Observatory) has still gaps and gives only the variations from day to day. The use of a photographic procedure, which gives immediately with one exposure field-strength and polarity for all spots, also for the smaller ones would be of great help.

The measurement of smaller fields outside the spots has made great progress during the last years [3]. The circular polarization produced in the two wings of a suitable Fraunhofer line is measured photoelectrically. Mostly the iron lines λ 5250 and λ 6173 are used. The wings of the line are separated by a large grating spectrograph and their light is proceeded to two photomultipliers. No details about the measurement can be given here. The smallest magnetic field still detectable on the sun follows from the condition, that within the time of measurement (*e.g.* 1 s) the natural fluctuation of the photocurrents i in the two multipliers ($\sim \sqrt{i}$) will have the same amplitude as the signal Δi produced by the polarization of the wings of the line. Consequently the smallest detectable field-strength depends upon the light flux or photocurrent in the wings. This current is defined by the aperture of the prime objective of the telescope and by the size of the scanning spot on the sun. By increasing the aperture of the telescope, a smaller scanning spot can be applied. But doing this also the disturbing effect of seeing will increase which in general will smear out the scanning spot to a few seconds of arc in diameter. Therefore it has in general no sense to have diameters larger than 30 or 35 cm. With a perfect instrument using a time constant of about 1 s and a scanning spot of 10" diameter a field of 1 gauss can still be measured. The use of a smaller scanning spot would need a longer time constant and this would increase the effect of seeing. Field measurements with a scanning spot of 1"

or 2" will be limited to fields > 50 or 100 gauss. This is quite unsatisfactory because most of the photospheric and chromospheric structures have dimensions around 1".

A further limitation is the fact that under 100 gauss only the longitudinal component of the field can be measured. By this the direction and the absolute strength of the field-vector in most cases will be unknown.

A new photographic procedure first applied at Mt. Wilson Observatory by R. B. LEIGHTON [4] might be mentioned here, because it probably will be able to record the fine structure of the solar magnetic fields, at least for longitudinal fields > 30 gauss. He takes simultaneous spectroheliograms in the two wings of a magnetic line. By using a photographic differential method he succeeds in producing from these two spectroheliograms a single picture which shows the distribution of fields in the form of bright and dark regions corresponding to the polarity of the fields. He obtained a resolution of $\sim 3''$.

For all field measurements, based on the Zeeman effect, it must be remembered that the result obtained is the integral over the length, along which the absorption line is absorbed or emitted in the solar atmosphere. This means, that also in the line of sight a geometric uncertainty comes in.

3. - Description of the variable solar phenomena.

In the following all those optical phenomena will be described shortly, illustrated and named, which altogether represent the activity of the sun. With the aid of such a review it will be easier to discuss the life story of a C.A. To keep this survey simple and clear, certain details have been left out. The reader who wants to go deeper into the matter is referred to the special literature listed at the end of this paper.

3.1. *Photosphere.*

Granulation: The granulation occurs everywhere on the sun's surface and is not a product of solar activity, nevertheless it has a definite effect on several of the variable phenomena of a C.A. The granulation structure, as can be seen in Fig. 1, consists of elements of about 1" in diameter, which are about 30 times brighter than the space between them. The life-time of the granules is between 1 and 5 min. They are ascending stream cells with an inner velocity of about 0.5 km/s. The form of the cells seems to be almost the same everywhere, even close to sunspots. The granulation can also be observed occasionally in the umbrae of larger sunspots.

Sunspots: A sunspot consists of a dark nucleus—the umbra—with a temperature of about 4500° , surrounded by the penumbra, the brightness of

which is intermediate between umbra and undisturbed photosphere. The penumbra is built of filamentary, almost radially arranged structures, the penumbral filaments (length 2000 to 12000 km, thickness < 1000 km, life time several hours). Outside the penumbra begins the photospheric granulation.

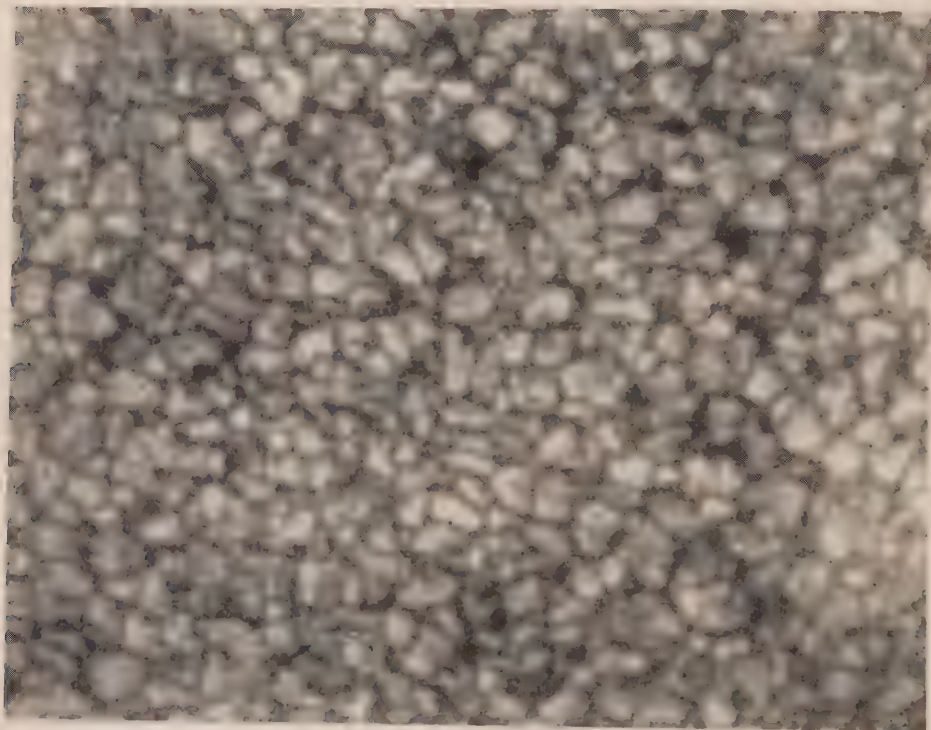


Fig. 1. - Solar granulation, scale 1 mm = 150 km on the sun. Picture taken from an unmanned balloon in 27 km height. M. SCHWARZSCHILD [1].

A spot which just has appeared has no penumbra and is called pore (diameter (1500 - 2500) km) during its first hours of life. The diameters of the umbrae are between 2000 and 20000 km, of the penumbrae between 4000 and 50000 km. The magnetic fields measured in the center of the umbrae vary between 150 and 4000 gauss.

Sunspots show a pronounced tendency to form groups, which develop within 10 to 20 days to their maximum size, about 200000 to 300000 km east-west extension and 60000 to 80000 km north-south. The number of single spots per group climbs occasionally over 100.

The large majority of spot groups develop already after a few days into bipolar groups, which consist of two main spots of opposite magnetic polarity and many small spots.

The spot groups are according to the Zurich classification classified into the following types *A* to *J*, which also give the consecutive stages of development of a large sunspot group: *A* — single spot; *B* — small bipolar group;



Fig. 2*a, b, c*. — Development of a spot group as seen in integrated light: *a*) spot group of class *B*, 2 days old; *b*) class *C* group, 4 days; *c*) *F*-group, 10 days.

C — bipolar group, main spot with penumbra; *D* — both main spots with penumbra; *E* — large bipolar group, numerous single spots; *F* — very large group, east-west dimension over 15° ; *G* — large bipolar group without small spots; *H* — single spot with penumbra; *J* — small single spot with penumbra.



Fig. 2*d, e.* — Development of a spot group as seen in integrated light: *d)* *G*-group, 18 days; *e)* *H*-spot, 25 days.

A few of these classes are presented in the Fig. 2. The sunspot number is defined as

$$R = K (10g + f),$$

where *f* is the number of all visible single spots and *g* the number of groups, *K* a coefficient which permits to reduce counts to standard conditions. The sunspot number depends strongly upon the seeing conditions and the helio-centric position of the earth. For these reasons it cannot be called a solar measure of the sun's activity.

In the penumbra and in the very surrounding of sunspots in rapid evolution thread shaped loops, called photospheric loops [5] occur, which are a little bit brighter than the background, have a length of ≤ 8000 km and a thickness ≤ 1000 km. Also the so-called light bridges, which sometimes divide the umbrae have a similar thread structure and exceed the brightness of the undisturbed photosphere considerably. Examples of such structures are given in Fig. 3 and 4.

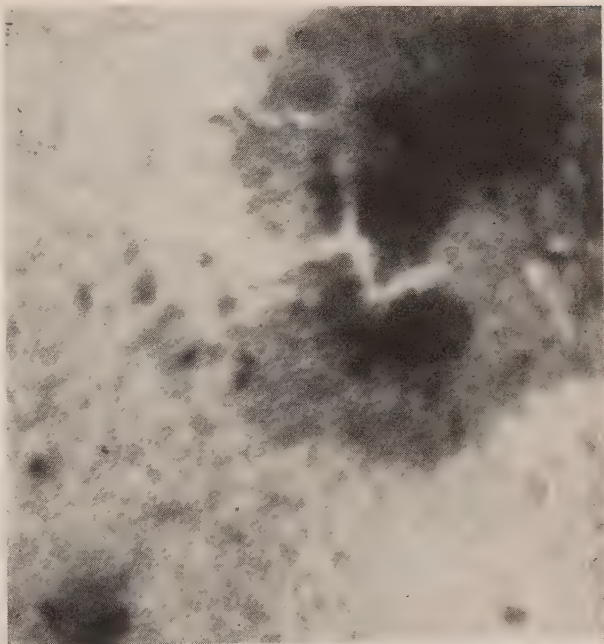


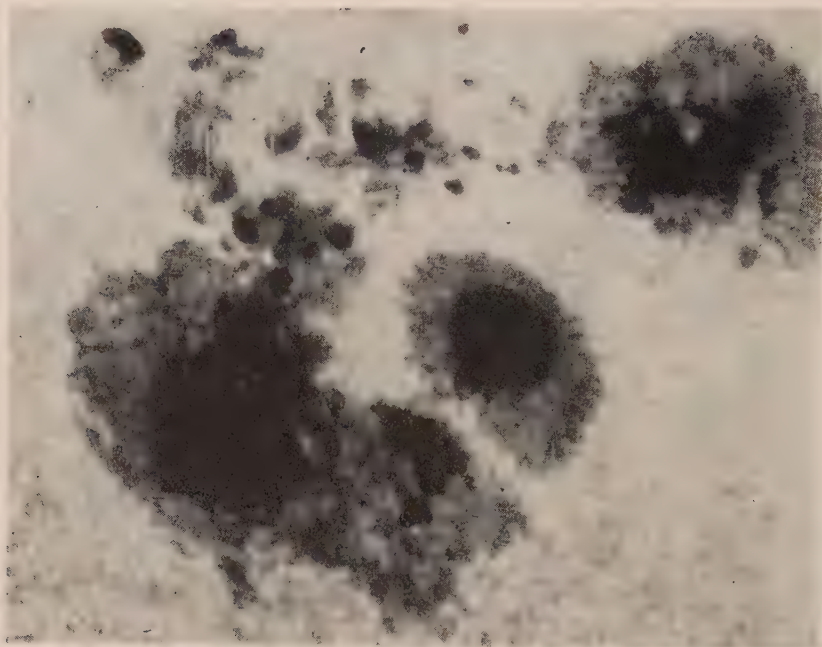
Fig. 3. — Light bridges in sunspots (Fraunhofer Institute).

Photospheric faculae: In integrated light

faculae can be seen only close to the sun's limb, while in monochromatic light (H_{α} and K) all over the disc. The first are called photospheric, the latter chromospheric faculae, in spite of the fact that both represent more or less the same phenomenon and coincide within a C.A. The photospheric faculae appear exclusively as bright dots, sometimes arranged in chains, diameter of single element about $1''$, life-time of 10 min to about 1 hour. They appear only in a C.A. or in the close vicinity of sunspots. The life-time of the whole facular region however exceeds even that of the associated sunspot group considerably.

Photospheric magnetic fields: The optical measurement of magnetic fields is confined in general to photospheric layers. Our ignorance of fields outside these layers however does not mean, that there are no fields.

B. M. regions: According to the BABCOCKS [3] B.M. regions are bipolar field patches of 50 000 to over 200 000 km in diameter and fields of ~ 1 to 50 gauss. The distribution of polarities in these regions is the same as for sunspots, which always are formed in a B.M. region. The positive and the negative flux of such a region is about the same. The life-time of such a field patch exceeds that of the spots and even that of the associated faculae. Sometimes it is longer than 10 solar rotations. According to R. B. LEIGHTON (l. c.)



↑
Fig. 4. — Photospheric loops, best visible under the large spot on the right (Fraunhofer Institute).

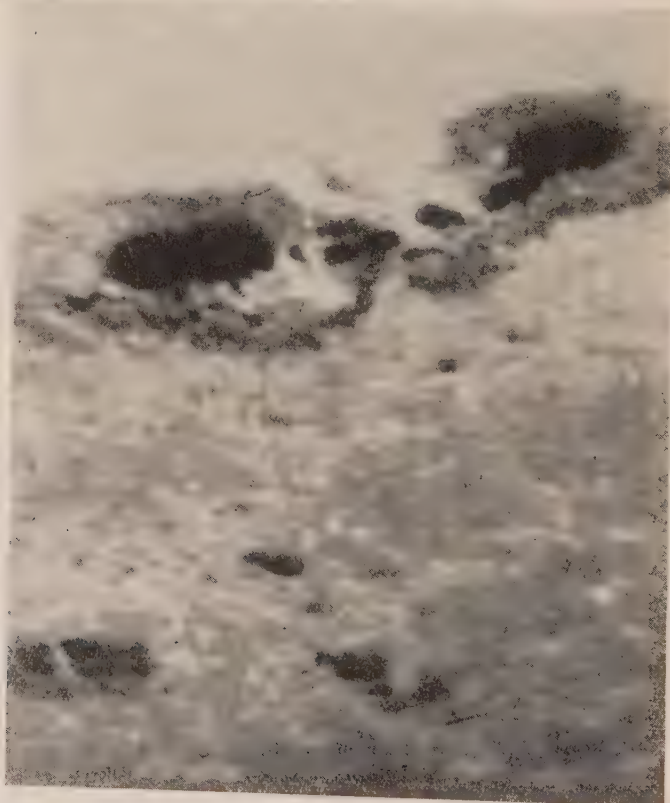


Fig. 5. — Photospheric faculae near the sun's limb (Fraunhofer Institute).

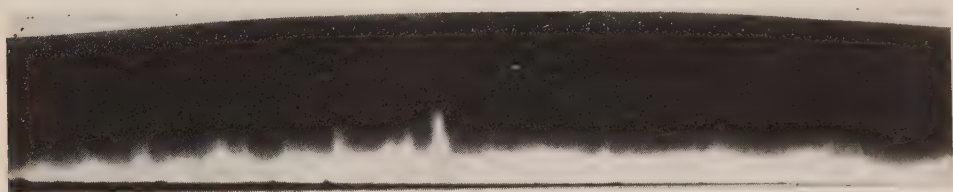
it might be, that the field is not distributed smoothly, but flows out in form of a network, the same which can be seen in K and H_α and along which the spiculae appear.

M. M. regions: They are multipolar regions, which are rather rare, while unipolar regions do not seem to exist at all, except as the very last, still just detectable traces of a B.M. region.

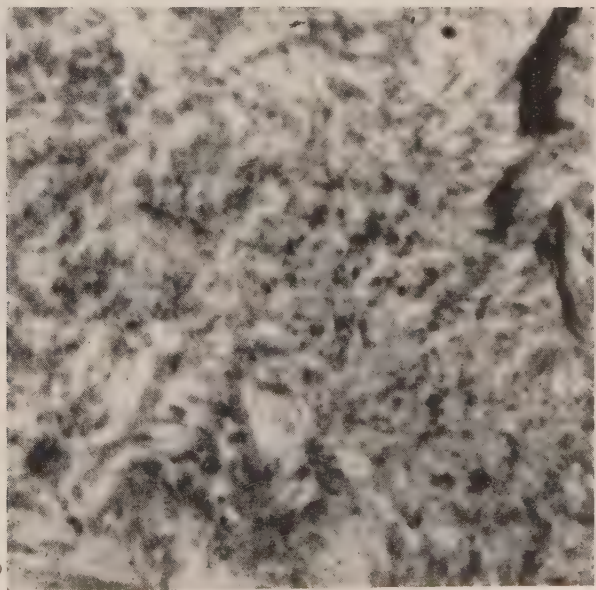
Within these magnetic regions large field fluctuations can be observed already in one hour. However reliable details about these field changes will be available only, when the scanning spot of the magnetograph will be comparable in size with photospheric structures, because they must be the carriers of these fields. It is not yet known, whether the granules carry their own magnetic field.

3'2. Chromosphere.

Spicules: As seen on the sun's limb they shoot almost radially into space as bright little tongues (H_α), about 20 or 50 of them visible at a time. Their velocity of ascent is about 30 km/s, their life-time 3 to 5 minutes,



a)



b)

Fig. 6. - a) Spicules on the sun's limb (Sacramento Peak Observatory); b) spicules on the disk (H_α filtergram Fraunhofer Institute).

their height up to about 10 000 km, their thickness 500 to 2 000 km. They appear all around the sun, but are a little bit more numerous in polar latitudes. They show systematic inclinations, in most cases towards the equator. On the disk spicules appear in H_α as dark dots, diameter 1' to 3', at a time

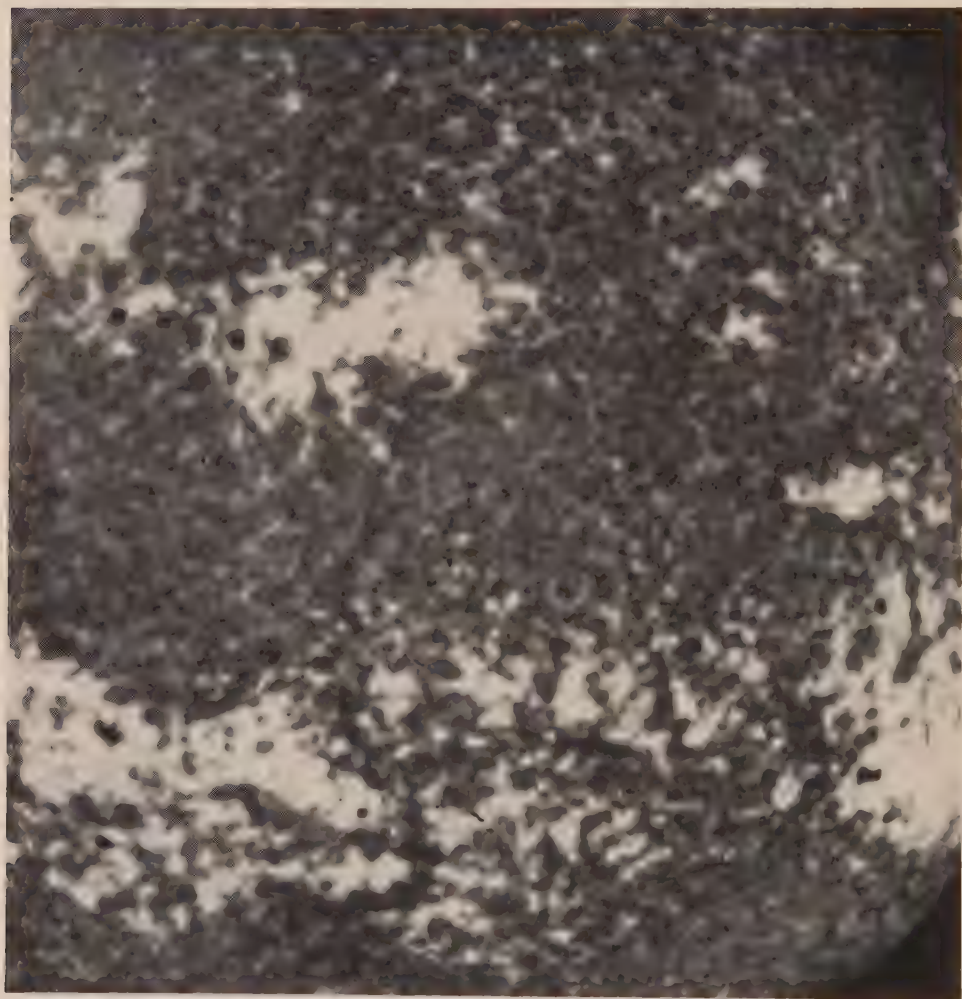


Fig. 7. - Calcium network on the sun (K -spectroheliogram Fraunhofer Institute).

about 15 000. Towards the sun's limb their form becomes elongated. In Fig. 6 samples of spicules on the limb and on the disk are given. On the disk the spicules are arranged more or less regularly in a kind of network, the general form of which can be recognized even after a day. In spite of their short duration the spicules are bound to certain longer-lived configurations. This

network and therefore also the spicules coincide with the bright network formed by the K -facular dots, called bright mottles (see Fig. 7). Occasionally groups of spicules are clustering together forming larger structures of more than 3 000 km in diameter, called coarse mottles.

The network of the spicules reaches into the C.A.'s and will be disturbed sensibly only close to spot groups. Spicules are cool formations ($\sim 10\,000$ to $40\,000$) imbedded in the inner corona ($\sim 100\,000$). Their density probably does not differ too much from that of the surrounding corona ($\sim 10^{10}\text{ cm}^{-3}$). Within the C.A.'s the spicules are strongly deformed, about as waterplants

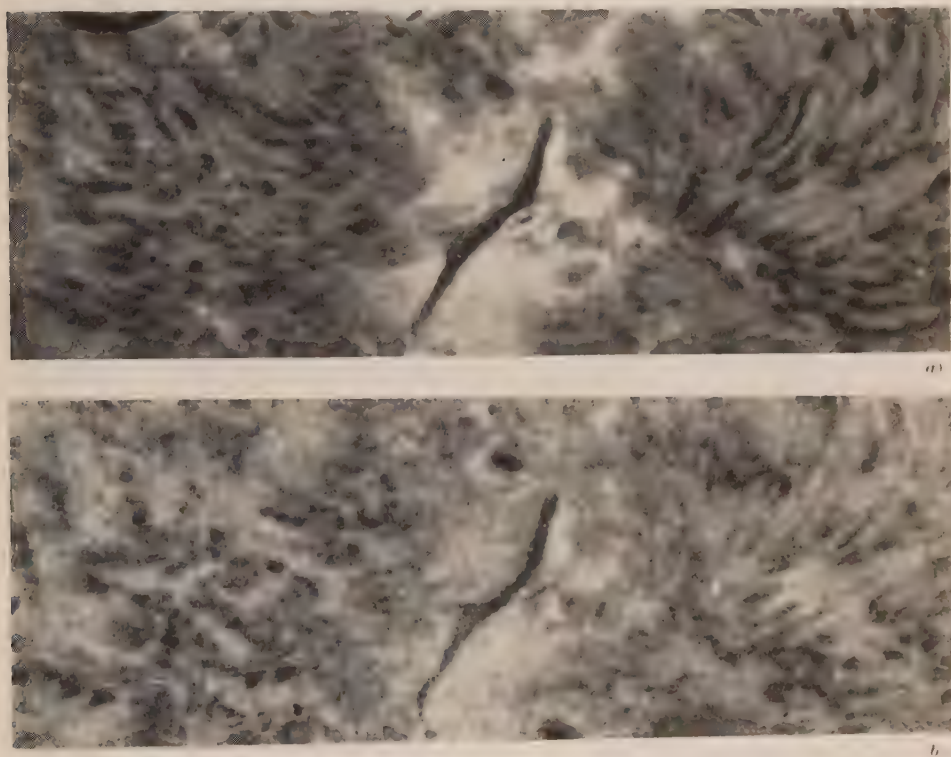


Fig. 8. — Spicules in a center of activity: a) center of H_{α} ; b) wing of H_{α} .

in a streaming water are oriented all parallel. Fig. 8 shows a typical example, as seen in the centre and in the wing of H_{α} .

Chromospheric threads: Threadlike structures which can be seen only in H_{α} are formed in every C.A. from the very beginning on [5]. Often they connect the penumbrae of the main spots of opposite polarity of a bipolar group, mostly in the form of bundles, which surround the bright strand of faculae also connecting the main spots. These threads are continuous struc-

tures without break. Their length is 20 000 to 100 000 km, their thickness — 1 000 km. In most cases it might be under the resolution of the instrument. An example is given in Fig. 9. The threads appear in the center of H_{α} a little bit brighter than the photospheric background.

Some of the threads connect the penumbra of one spot with a point of the surroundings or connect two points outside the spots within a C.A. But always the threads end then on the network, which is formed by the spicules (dark in H_{α} , bright in K). The deformed spicules seem to merge into the threads. Always the threads follow a general pattern of alignment, which altogether

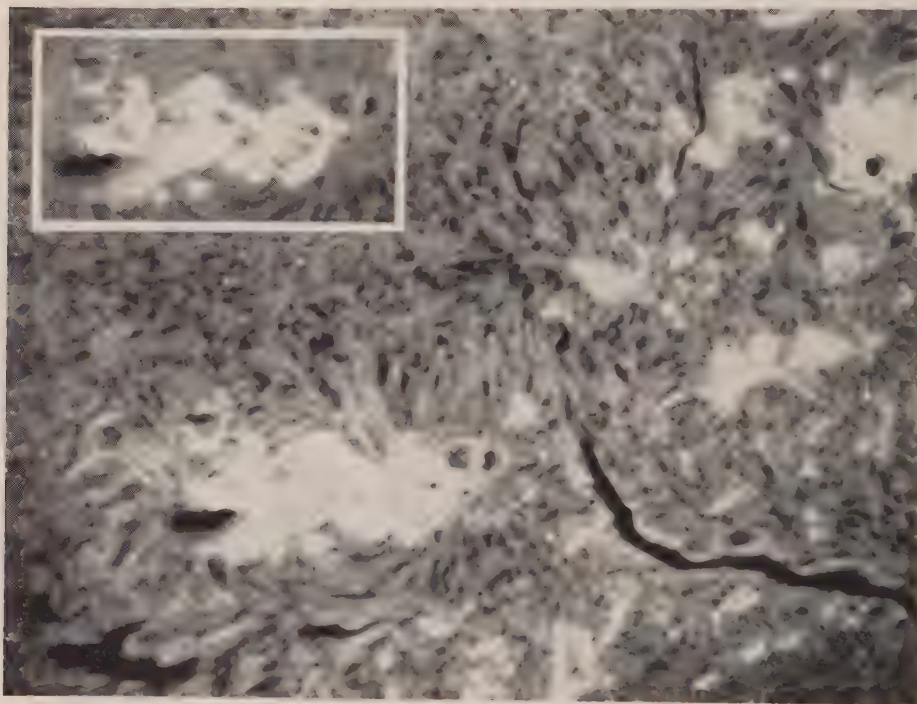


Fig. 9. Chromospheric threads in a center of activity. In the small picture the facular strand is reproduced again, to show better its thread structure.

represents the structure of the C.A., sometimes forming waves or loops, similar to those seen in the photosphere. An example is given in Fig. 10. The total configuration of the threads changes very little from day to day. However, the single structure shows a billowing motion already within an hour.

Spectroheliograms or filtergrams with insufficient resolution (more than 3') do not permit to distinguish between the bright threads and the darker intervals between them. Quite often these intervals have been considered as real structures (fibrilles), while the threads were taken as the structureless background [6].



Fig. 10. Samples for chromosphere loops: a) in a region without sunspots.



Fig. 10. — Samples for chromospheric loop $\times$ b) in the vicinity of a flare.

Also filaments or prominences are connected by threads with the chromosphere, which differ in nothing from the described threads, except that they reach sometimes far into the corona. There can be little doubt, that all the thread structures as seen in H_{α} are like the spicules cool bodies surrounded by the much hotter corona which apart from the prominence threads occur in a very flat layer, the height of which might be under 5 000 km.

Chromospheric faculae: Faculae are bright structures, which can be seen in H_{α} , K and close to the solar limb also in integrated light. The formations which can be seen only in Fraunhofer lines are called chromospheric faculae, those visible in white light photospheric faculae. Sunspots are always accompanied by faculae. A small fraction of faculae also appears without spots.

In H_{α} one can distinguish within a C.A. two types of faculae. Scattered all over the region bright dots with a diameter of 1 000 to 2 000 km, which often cluster in groups or chains, as can be seen in Fig. 11. These H_{α} dots coincide with similar structures in K and also with the bright dots seen in integrated light (only close to the limb). The general configuration of these dots changes little from day to day, the life-time of the single dot is of the order of a few hours. The bright H_{α} -dots however are not numerous enough to fill out the regular network formed by the bright K -mottles.

In the very vicinity of sunspots or in regions where sunspots are just coming to appear another type of faculae occurs, which has more a thread-like, sometimes also a patchy character, which is much brighter than the dots, the brightness being intimately related to the development of the associated spot group. The dimensions of these bright regions amount to 5 000 to 50 000 km. Both types of faculae are well recognizable in Fig. 11.

In the K -line the faculae appear in quite a different form: The whole disk of the sun is covered with a bright network as seen in Fig. 7, meshwidth of about 25 000 to 50 000 km, the brightness of which increases strongly when approaching a C.A. This network is built of small bright dots, which seem to coincide with the spicules as seen in H_{α} . Within the C.A.'s the K -faculae have a more patchy, floccular character, sometimes covering the spots. These bright features obviously coincide quite exactly with regions of strong longitudinal magnetic fields. This type of faculae, which overlaps with the less extended H_{α} -faculae always avoids regions where the H_{α} -threads are observed. The life-time of these faculae close to the spots exceeds that of the spots considerably and might be over 200 days. The magnetic B.M.-regions producing these bright K -patches have still a longer life-time.

Special attention must be given to the short lived flarelike faculae which appear during the sudden ascension of a filament (sudden disappearance=S.D.) along the filament in the form of a chain of bright mottles. They brighten up about 30 min after the departure of the filament and fade a few hours later [7].

Flares: Flares are sudden brightenings, which can be seen almost in all Fraunhofer lines, especially in H_α and H_β , sometimes also in integrated light. They appear always in C.A.'s, in about 5% of the cases without sunspots. The

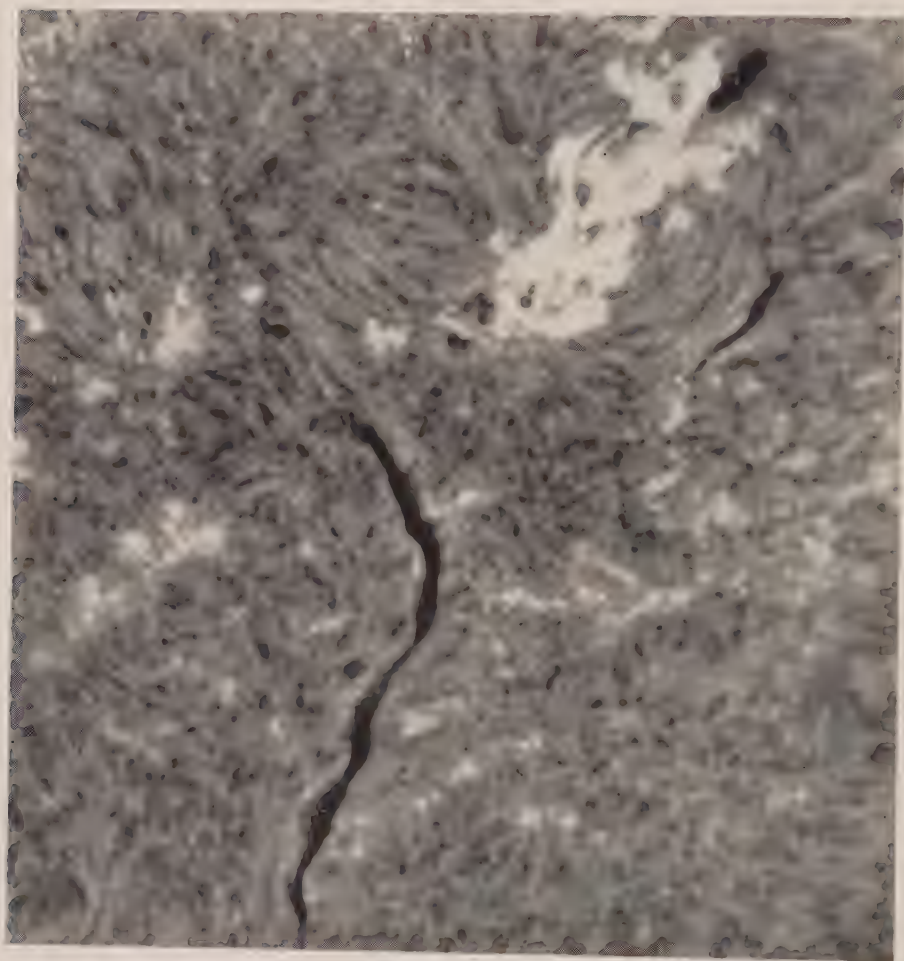


Fig. 11. Types of chromospheric filaments in center of activity. On the right a bright filamentary strand within a bipolar spot group, on the left filament dots, arranged in chains (H_α -filtergram Fraunhofer Institute).

bright area of a flare amounts to (70–1000) millionths of the sun's visible hemisphere or $55 \cdot 10^6$ to $1000 \cdot 10^6$ km². The classification of flares is mostly based on their area, reduced to the center of the sun's disk. The following table gives some information about flares of different importances. The intensity in the center of H_α is given in units of the adjacent continuum.

Importance	Area 10^{-6} vis. hem.	Linewidth H_{α}	Intensity center H_{α}	Relative frequency
1 —	< 100	1.5	0.6	—
1	100 ÷ 250	3.0	0.8 ÷ 1.5	0.72
2	250 ÷ 600	4.5	1.2 ÷ 2.0	0.25
3	600 ÷ 1200	8	1.4 ÷ 2.5	0.03
3+	> 1200	15	2 ÷ 3	—

For the sake of simplicity the classification is a very primitive and rough one, in spite of the fact that the phenomenon of a flare, its form, its brightness, its spectrum varies in a very complex manner with time. Especially in the larger flares different areas become luminous successively, each following its own light curve, which in general rises steeply within a minute and decays slowly within 10, 20, 60 or 100 minutes. Sometimes the luminous part is creeping along existing chromospheric structures, enlightening them on its way. In such cases the total area of the flare or its total brightness in H_{α} as a function of time will be rather a poor representation of what really happens. To get an idea of the variety of forms, some examples of flares are reproduced in Fig. 12.

There is not yet general agreement, in what height in the solar atmosphere a flare can occur. From observations on the limb it follows, that some flares appear to be almost detached from the chromosphere, others are definitely connected with it. In general one must assume, that a flare similar to the other chromospheric structures is surrounded by the corona and is also a cool body ($10\,000$ to $15\,000^{\circ}$) inbedded in coronal gas ($> 100\,000^{\circ}$). A temperature of $15\,000^{\circ}$ does not exclude of course the occurrence of a small fraction of particles with energies $\gg kT$, *e.g.* $> 10^9$ eV, as they are supposed to be generated in a flare as cosmic ray particles.

Flares occur mostly in the very vicinity of variable spots, preferably within the first 10 to 15 days of the spot group's life. In spot groups which develop to full size, as much as about 50 flares can be observed. Flares show a certain tendency to reappear in the same regions, resp. to brighten up along the same chromospheric structures again. It further seems important to note, that the occurrence of a flare does not change the chromospheric structures observed in its area, at least not more than by a few seconds of arc.

The brightest parts within a flare are dots and lines. These are surrounded by a more diffuse luminosity, in which sometimes expanding motions up to 100 km/s are observed.

According to SEVERNY [8] changes of the longitudinal component of photospheric magnetic fields are observed. It is however an unsolved problem how

this result can agree with the finding that chromospheric structures in the flare region do not change.

Recent results obtained at Mt. Wilson by HOWARD [9] however do not confirm Severny's results.

Flares sometimes occur almost simultaneously in different C.A.'s with a probability which is certainly higher than by chance [10]. The observations

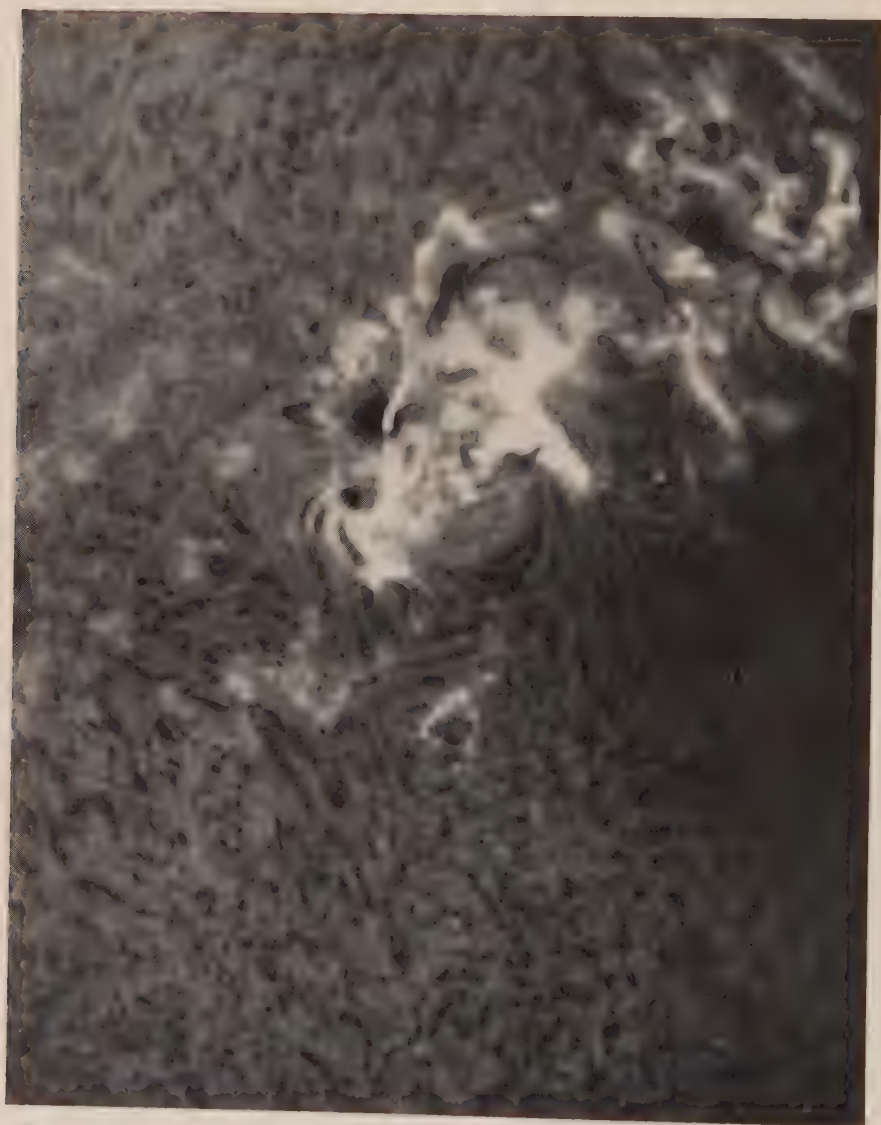


Fig. 12. Solar flares. Flare of importance 3, Nov. 7, 1956 (18 S; 31 E, 11.04 h - 13.54 h);
a) 11.39 h.

are best represented, when it is assumed, that every flare in the source of a perturbation, which propagates with a velocity of about 1000 km/s and which is able to trigger flares in other appropriate places. This action on distance reaching over a full hemisphere of the sun or more can be understood only if the energy transported by this wave be quite remarkable. It might be that the start of this perturbation coincides with the so-called flare

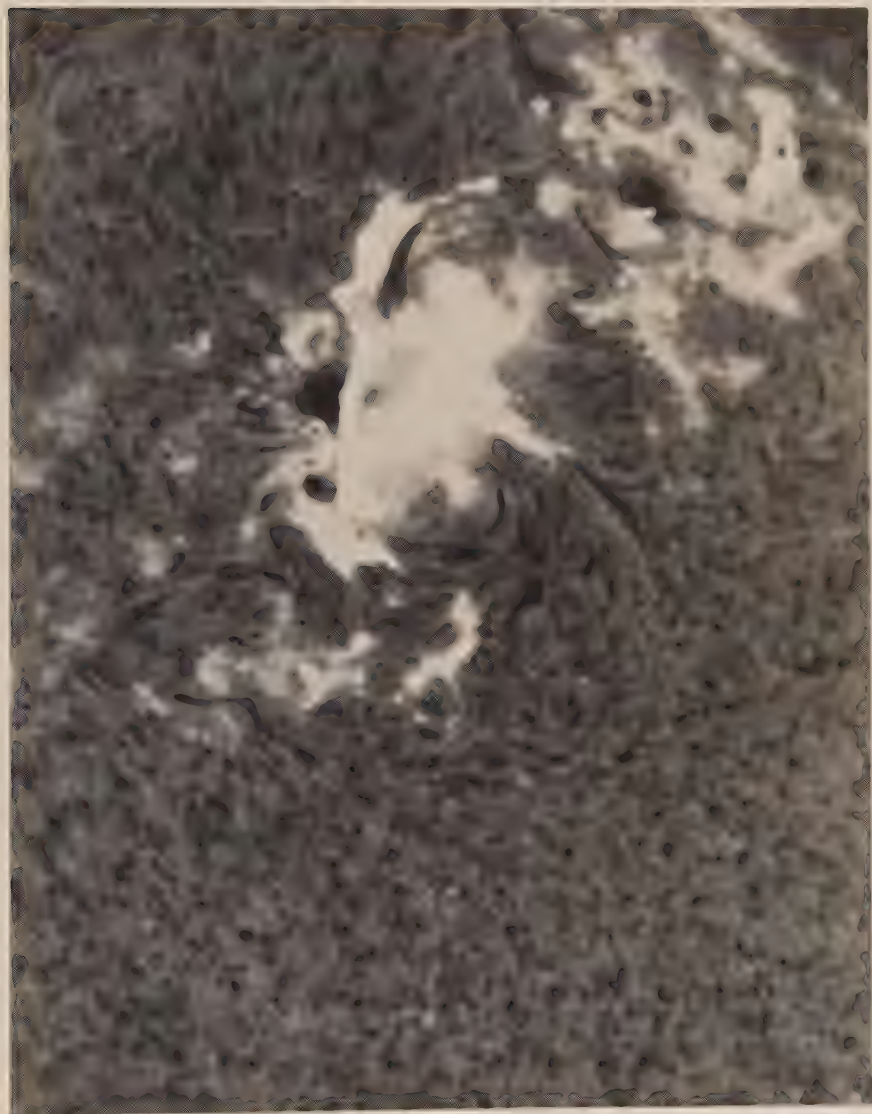


Fig. 12. Solar flares. Flare of importance 3, Nov. 7, 1956 (8 S; 31 E, 11:04 h - 13:54 h)
A) 12:17 h.

puff [11], a rapid expansion of the flare. The type II radio bursts, which also are due to an agency travelling with 1000 km/s might be related to this event.

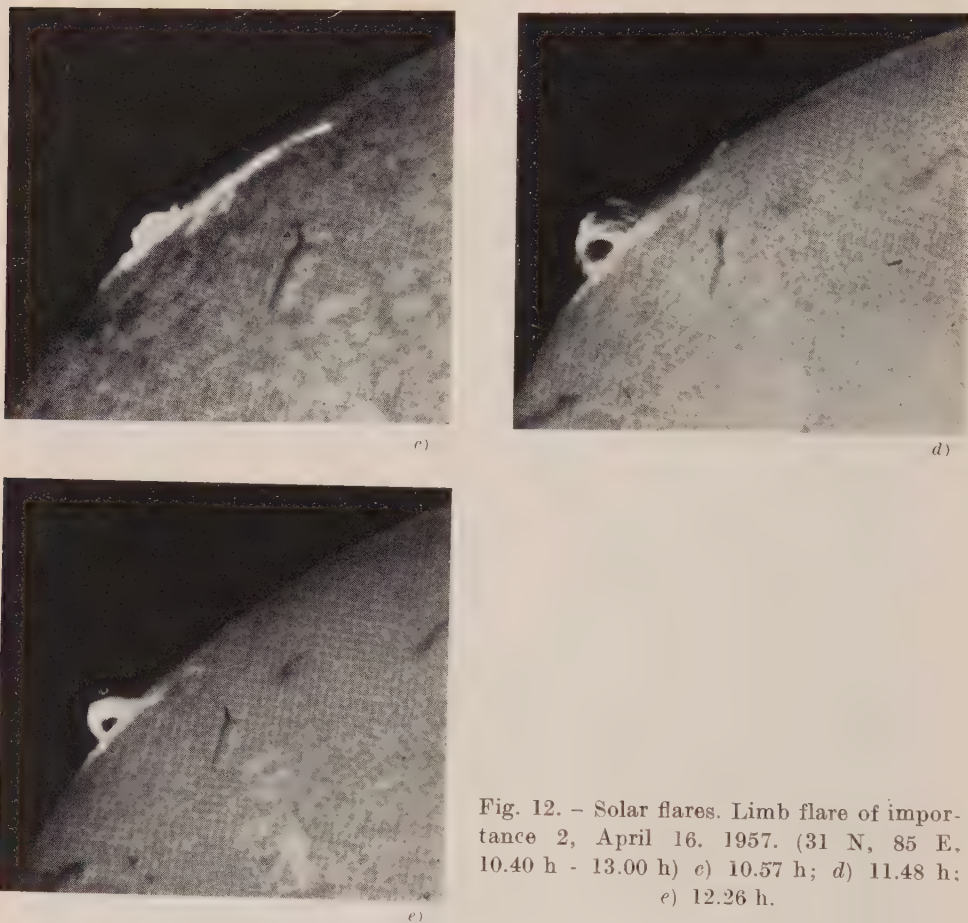


Fig. 12. - Solar flares. Limb flare of importance 2, April 16, 1957. (31 N, 85 E, 10.40 h - 13.00 h) c) 10.57 h; d) 11.48 h; e) 12.26 h.

Moustaches: Flares are best visible and brightest in the center of H_{α} , while moustaches mostly emit in the wings of the line [12], which can have widths of more than $10 \text{ \AA}$. The term moustache applies to the wing structure in the spectrum. They obviously are emitted in the low chromosphere. They further show a continuous emission, which runs all over the spectrum. In the wing of H_{α} they appear as a little bright dot, diameter $1''$ to $2''$ on the edge of the penumbra with a life-time of a few minutes, sometimes several per hour. From the wing profile it is concluded, that in a moustache velocities up to 1000 km/s can occur. The russian workers assume further, that flares are partially built of moustaches.

A certain similarity to moustaches have the « Ellerman Bombs », which

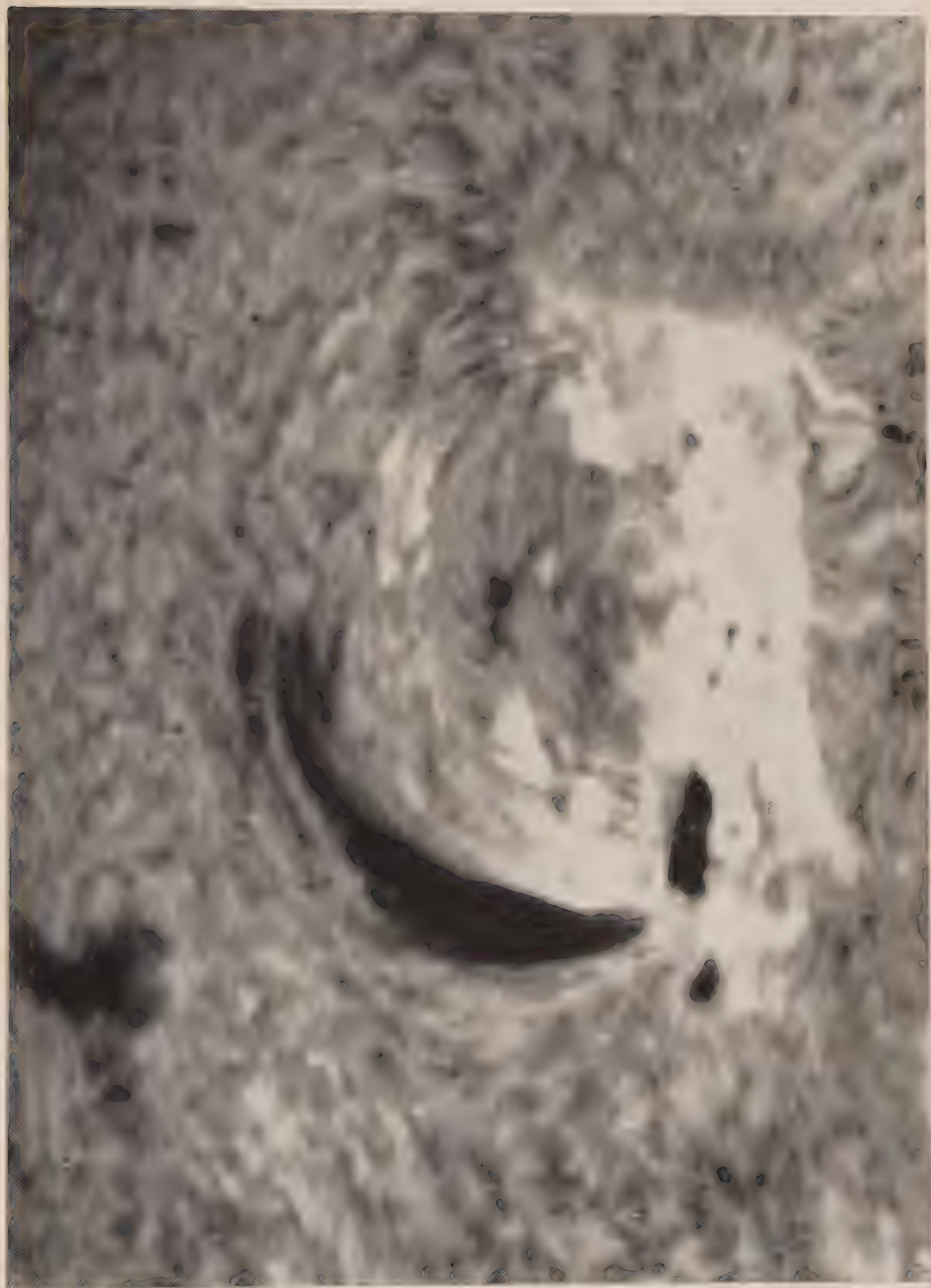


Fig 13 - Flare surges: a) flare surge on the disk. (H_{α} -filtergram, Fraunhofer Institute, March 19, 1959).



Fig. 13. - Flare surge: *b*) same as *a*), but photographed in the violet wing of H_{α} .

have however a much longer life-time and which probably come from still deeper layers.

Flare surges: Surges are ejections of matter into the corona which can best be observed in H_{α} . There are the so called bright and dark surges, according to their intensity relative to the sun's disk. Outside the sun's limb they appear always bright, mostly brighter than prominences. On the disk they come mostly as dark features, only in regions closer to the limb they reach or exceed sometimes the brightness of the background. Their starting point seems to be always in the chromosphere or may be somewhat higher. No surge detached from the sun's body has been observed on the limb. They

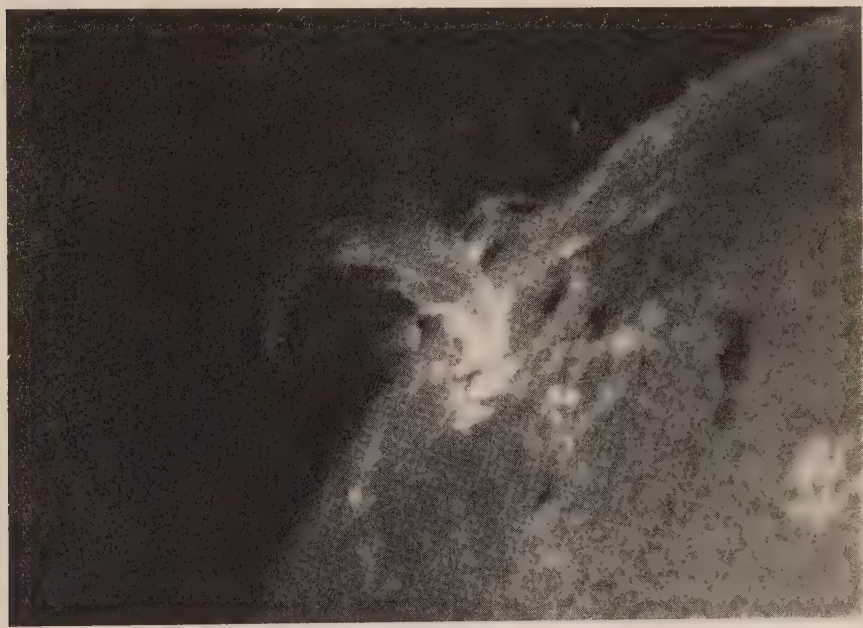


Fig. 13. - Flare surges: c) flare surge on the limb of the sun (H_{α} -filtegram, May 15, 1957, Fraunhofer Institute)

occur more frequently and more violently in the vicinity of flares and are called flare surges then. Often the ejected matter returns to the chromosphere along the same trajectory along which it was thrown but, no matter whether the trajectory is curved or linear. The velocity of ejection is on the average under 150 km/s, but sometimes more than 300 km/s. The velocities of return are much smaller. The ejections have a tendency to repeat on the same place in the chromosphere, following again the same path in the corona.

Most of the flare surges are seen first a few minutes after the onset of the associated flare. In some cases however the surges started definitely before



Fig. 1 . - Flare surges: *d*) flare surge on the limb of the sun, showing a thread structure. (H_{α} -filtergram, April 18, 1957, Fraunhofer Institute).

the flare. The larger the importance of the flare, the greater the probability that a surge will occur (Importance 1, 31%; Imp. 2, 51%; Imp. 3, 80%).

All larger surges seem to be split in a number of fine threads, the thickness of which must be $\leq 1''$. For this reason they are rarely well resolved. In Fig. 13 few examples of flare surges are represented. The trajectory of a surge when ejected under a flat angle to the sun's surface follows exactly the general pattern of chromospheric structures and therefore also the magnetic field. Also the fact, that a surge preferably is directed away from the next larger spot speaks in favour of this conclusion.

From the observations hitherto made, it does not follow whether really chromospheric matter is ejected or whether a surge is formed by the densification of coronal matter. Sometimes surges appear first in emission outside the sun's limb, while on the disk they become visible in absorption only ~ 10 minutes later [13]. From this one might conclude, that surges are of coronal origin and cooled down to chromospheric temperatures and densified in the corona [14].

Parts of surges become visible in white light during short intervals [15]. If this absorption is produced by the scattering of free electrons, their density should be of the order of 10^{13} cm^{-3} . The average density of a surge however is probably only 10^{10} to $10^{11} \text{ H atoms/cm}^3$.

Prominences. Outside the sun's limb prominences appear in H_α bright on a dark ground, when seen in projection on the disk they look dark, forming long structures, called filaments. The composition of the views obtained from

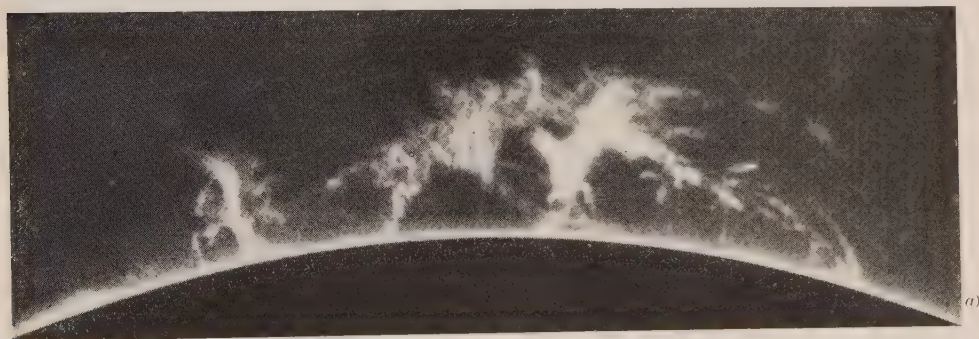


Fig. 14. — Solar prominences: a) prominence on the sun's limb (H_α -filtergram, Meudon).

the same prominence on the disk and on the limb leads to the following three-dimensional picture: Imbedded in the corona (10^6 degrees) a cool gaseous formation ($\sim 10^4$ degrees) which fills a volume in the form of a wall, standing almost vertically on the sun's surface, length 20 000 to 200 000 km, height 20 000 to 50 000 km and a thickness of only 5 000 km. This volume is occupied with a system of threads (diameter ≈ 1000 km) and knots. Apart from

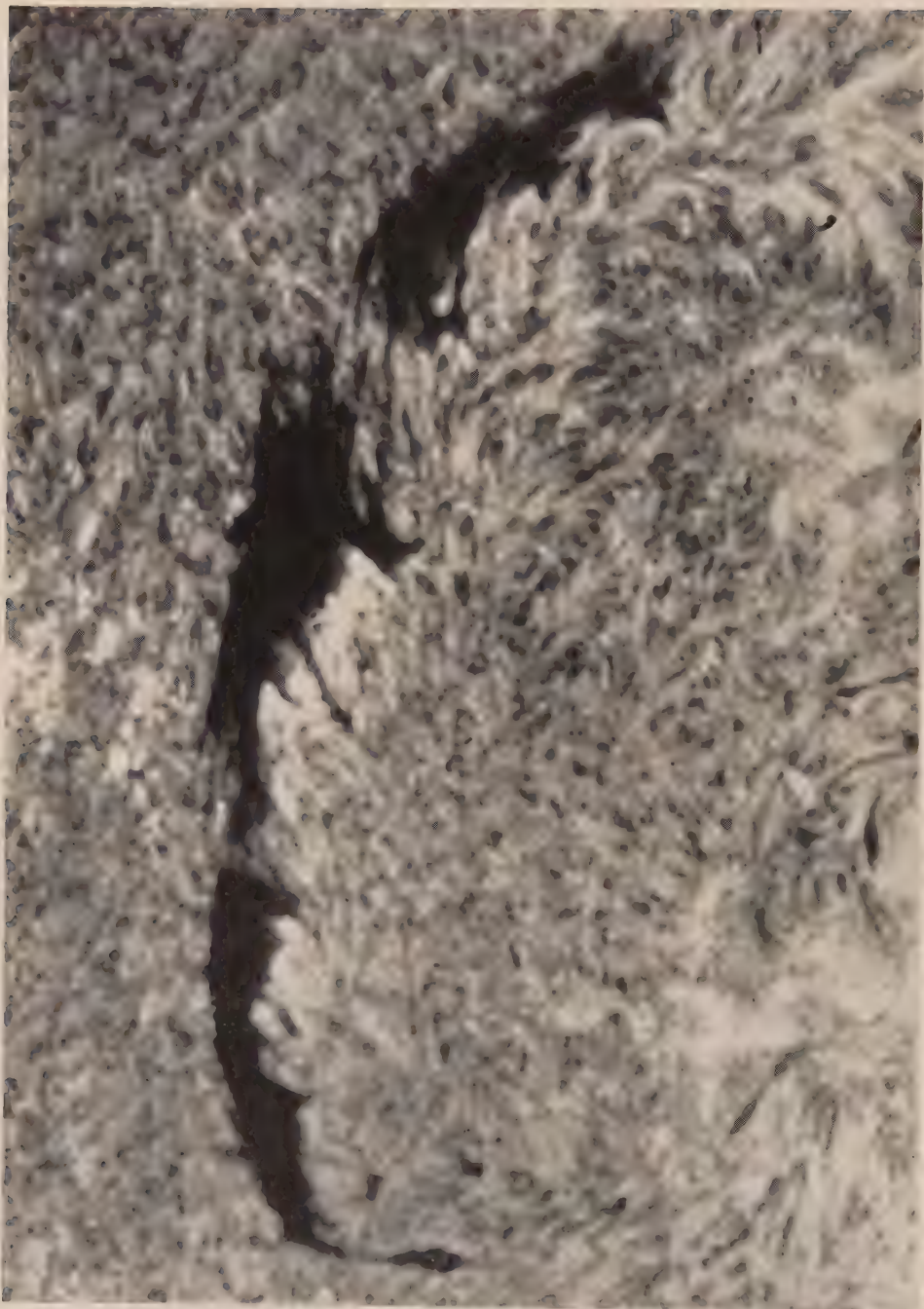


Fig. 14. - Solar prominences: *b*) prominence in projection on the disk (filament) (H_{α} -filtergram, Fraunhofer Institute).

a systematic growth of the filament in length ($\sim 100\,000$ km per solar rotation) it conserves in general its shape despite of violent internal motions.

The classification of the great variety of prominences distinguishes clearly between prominences close to sunspots which in general vary rapidly in form and those far away from sunspots, which have grown to a great length and which are stable. Also steady and moving prominences are distinguished. Further their form is taken into account, mainly according to their aspect on the sun's limb (funnel, loop, tree trunk, tree, hedgerow, mound, coronal rain, etc.). In Fig. 14 typical views of prominences on the disk and on the limb are given.



Fig. 14. - Solar prominences: c) spot prominences (H_{α} -filtergram, Sacramento Peak).

In some prominences when inspected on the sun's limb, more matter seems to stream down into the chromosphere than ascend into the corona. One must conclude therefore, that occasionally matter will be supplied to prominences from the corona.

Prominences always are formed first in the spot belts, sometimes close to a spot, sometimes in regions without spots. They start as a small feature changing shape rapidly, which sometimes becomes stable eventually after some weeks. Then it starts growing systematically in length. It then will survive all other phenomena observed in a C.A. Because of the differential rotation of the sun the filament turns slowly into the direction of the parallels. After

200 or 300 days, when it has reached its maximum length of a few 100 000 km it starts to decay.

All prominences or filaments are connected with the chromosphere by a complicated system of threads, thus forming an important bridge for the exchange of matter between chromosphere and corona and vice versa.

The photospheric magnetic fields measured in the surrounding of stable filaments and the general character of internal motions of prominences leaves no doubt that their form is defined by magnetic fields. Even the thermal stability of the cool prominences in the hot corona cannot be understood without the thermal isolation of the prominence against the corona by suitably directed magnetic fields.

In the course of their life prominences pass several critical periods: The so-called activation consists in a rapid increase of internal motion, which can go on for hours or days and often results in a strong downstreaming of matter into the chromosphere. Sometimes this leads to a complete disintegration. After some days such a prominence might be formed again, on the same place and with roughly the same shape.

Almost every filament becomes eruptive one or several times during its life. It starts ascending and disappears into space. Often also this filament will be replaced by a new one after a few days, which is similar in form. These ascensions are obviously the outcome of sudden changes of magnetic fields (appearance of a sunspot etc.) which pushes matter away because of induction currents. The same currents might be as well responsible for the flarelike faculae which appear in the chromosphere during the acceleration of the filament [6].

3.3. *Coronal phenomena.* — The corona is a very extended gaseous shell around the sun with a gas temperature of about 10^6 degrees, the density of which is about $5 \cdot 10^8 \text{ cm}^{-3}$ close to the chromosphere, and $5 \cdot 10^3 \text{ cm}^{-3}$ at a distance of 3 solar radii. Shape, temperature and density vary in the course of a solar cycle. One distinguishes the minimum-corona (no sunspots), which is clearly stretched in the equatorial plane and the maximum-corona, which has a round form. For the different regions and types of coronal emissions the following terms are in use: L-corona emits mostly close to the limb the coronal lines from highly ionized elements as Fe, Ni and A. This emission amounts to about 1% of the total emission of the corona, which is about 10^{-5} of the sun's brightness. The K-corona is radiating continuous radiation, photospheric light scattered by free electrons. The Fraunhofer spectrum is more or less washed out by the high speed of the scattering electrons. The light is polarized. The F-corona becomes visible only far away from the sun and represents the sunlight scattered and reflected by interplanetary dust. Its light is slightly polarized and contains the Fraunhofer spectrum. The coronal phenom-

ena discussed here mostly occur in the L- and K-corona and especially in the very surroundings of the C.A..

Important phenomena outside the C.A. are the polar rays and polar plumes, which come out best during the sunspot minimum, especially in white light, but are also visible in $\lambda 6374$. The thickness of these rays close to the solar limb is of the order of 7 000 km, their life-time is about 1 day. There

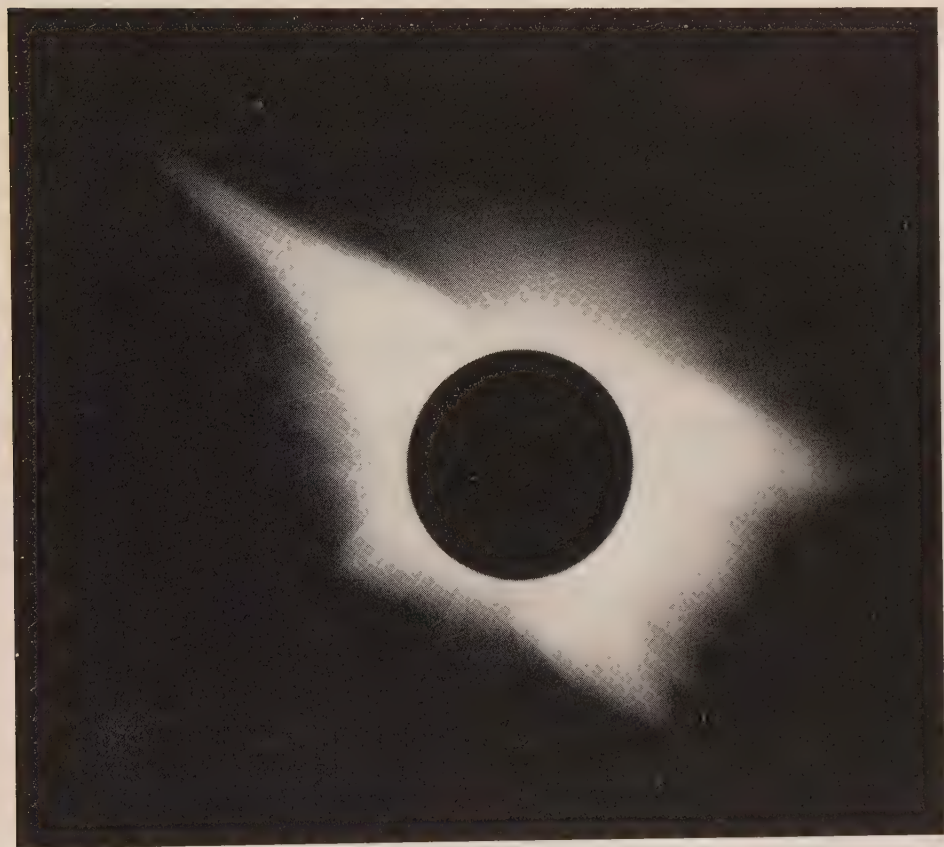


Fig. 15. - Coronal streamer. Total solar eclipse, February 25, 1952. (Photograph G. VAN BIESBROECK).

is probably no motion along the rays. They obviously represent the pattern of the sun's polar magnetic field.

A coronal streamer is a formation which goes out from the sun mostly radially, which can be traced in white light during an eclipse up to a distance of $\sim 12 r_{\odot}$. Close to the limb it has a width up to $1 r_{\odot}$ and shows concentric archs which often are centered around a prominence showing a dark space around the prominence. No important line emission is observed and there

is probably no conspicuous motion in the streamer. A typical example is given in Fig. 15.

The relation between filaments and corona in general is quite an intimate one: In an isophotic map of the corona as projected (from limb observation) on the sun's disk it follows [16], that the filaments are oriented parallel to the white isophotes and perpendicular to the isophotes in $\lambda 5303$.

In direct connection with the C.A. the following coronal phenomena have been observed:

Permanent coronal condensation: During the limb passage of a C.A. an electronic cloud is observed in the form of a calotte of 100 000 to 200 000 km diameter laying over the chromosphere. Its electronic density is 10 to 20 times the density of the undisturbed corona and amounts to $5 \cdot 10^9$ to

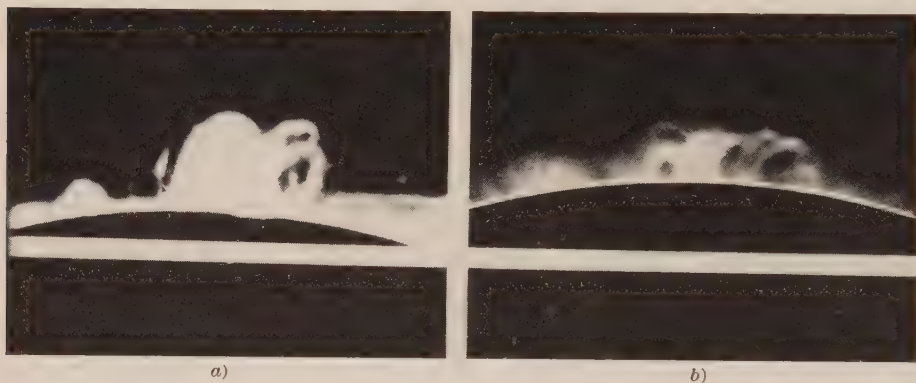


Fig. 16. Occurrences within a permanent coronal condensation: *a)* in H_{α} ; *b)* in $\lambda 5303$. (R. B. DUNN, Sacramento Peak Observatory).

$2 \cdot 10^{10}$ electrons/cm³. This « permanent condensation » is best developed when the associated spot group has reached the class *F*. Its life time is of the order of a few days. Within the condensation temperatures up to $(2 \cdot 10^6 \div 4 \cdot 10^6)$ degrees are observed.

Also within the condensation short rays (thickness $\geq 20\,000$ km) can be seen sometimes in the form of archs or in bunches.

In monochromatic light ($\lambda 5303$, $\lambda 6374$) the following features are seen above a C.A.

Concentric arches with sharp boundaries, the brightness of which decreases outward and which expand in the course of hours. Sometimes also rapid motions are observed (velocities up to 600 km/s). Simultaneously with these variations a rapid fluctuation of brightness is seen or the sudden development of a dark space with sharp boundaries. Sudden brightenings in $\lambda 5694$ occur in connection with flares. Short lived so-called sporadic condensations are observed within the permanent condensations in $\lambda 5303$ and 6374. Often they

coincide with H_{α} prominence-formations which appear very suddenly (knots, loops, funnels). They represent coronal regions, in which temperature drops very rapidly.

4. - Synoptical development of a C.A.

1st day: In an undisturbed region of the solar surface (homogeneous photospheric granulation, dark H_{α} -spicules and bright K -mottles are arranged in form of a network) a few of these structures become luminous in H_{α} , K and

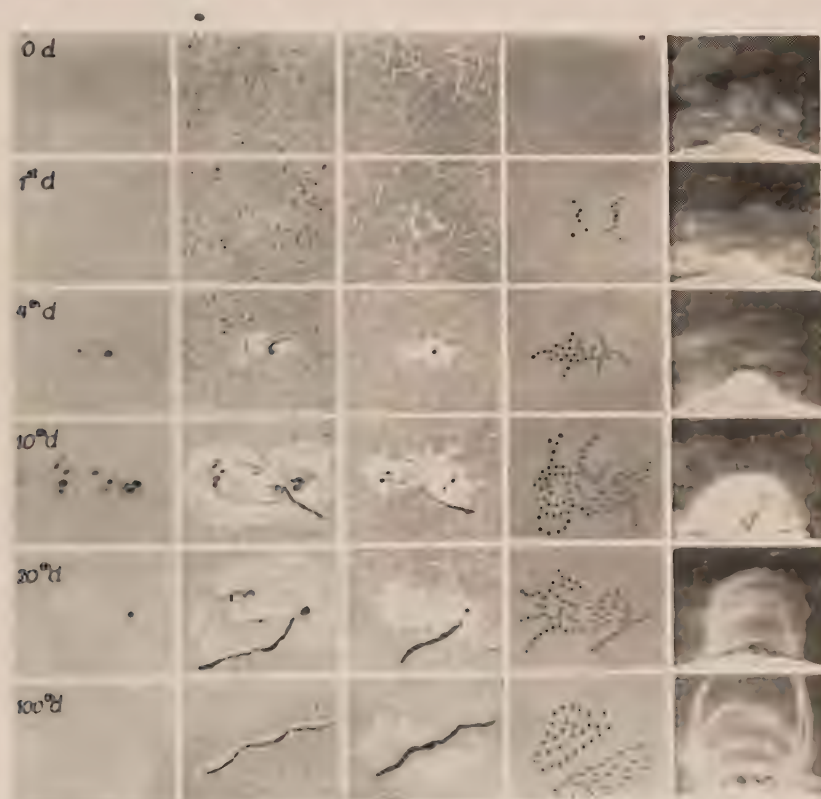


Fig. 17. - Simplified representation of the development of a center of activity for the first 100 days as it appears (from left to right) in integrated light, in H_{α} , in K , in the distribution of magnetic field and in the corona seen outside the sun's limb.

in integrated light (only visible close to the limb). The mentioned brightenings seem to form parts of one « cell » of the network. Simultaneously in the same region an increase of longitudinal magnetic field (> 50 gauss) is observed, probably already with bipolar character. About at the same time the first thread structures become visible in H_{α} . The small H_{α} mottles in the active region

developed rapidly into larger structures, more like bushes. The above threads flow into these bushes.

In Fig. 17 it is tried to sketch very roughly the development of a C.A. as seen on the disk and on the limb of the sun. Also the presumable distribution of magnetic polarities is given.

2^d day: Again on the network the first pores of spots are formed, quite often already in the form of a pair, with a distance of the order of 20 000 to 30 000 km (*). This is also the width of mesh of the network. Together with these first spots or even a few hours earlier a strand of bright faculae (H_λ and K) appear, the brightness of which exceeds that of the bright mottles of the day before. This bright strand already connects regions with longitudinal fields of opposite polarity and seems usually to be split in two halves by a dark lane, which looks like a small filament. The brightness of the corona above this region increases rapidly in $\lambda 5303$ (increase of temperature) and also in integrated light (increase of electron density). The H_λ -threads already form quite a bundle, which ends at the one side in the group of pores. At the other side the threads end along curved paths in one of the described dark H_λ -structures which by now are arranged in a kind of hedgerow forming a semicircle.

3^d day: In the middle of the above dark H_λ -structures another spot is formed of opposite polarity to the existing spot. The magnetic fields outside the spots have expanded. It is not yet known whether they cover the surface continuously or still are arranged in the form of a network. The facular strand has gained in brightness and area, especially in K . Also the corona has become brighter.

4th day: The western main spot is forming a penumbra, numerous single spots in bipolar arrangement are developing. The extension of the bipolar magnetic region is rapidly increasing. A first small filament is formed in the vicinity of the largest spot and fits well in shape and orientation into the pattern of the chromospheric threads, which surround the bipolar spot group up to increasing distances. The filament disappears still the same day. The densification of the corona has become brighter and more extended, its diameter on the solar surface might be more than 50 000 km. The first flares are observed, preferably in the vicinity of the larger spots. Simultaneously emission of the coronal line $\lambda 5694$ occurs. The smaller main spot in the east of the group is surrounded by a hedge of dark structures, into which merge many H_λ -threads, which come mostly from the western members of the spot group.

(*) According to an unpublished result of U. BECKER.

5th day: Also the eastern spot obtains a penumbra. The number of single spots has increased to about 20. Several flares are observed, mostly brightening along existing structures of the chromosphere. Flare surges are seen at the first time, dark on the disk, bright outside the sun's limb in the corona. As seen in projection on the disk, they follow the general pattern of chromospheric structures. A new larger filament has formed, which performs a kind of flagellant motion within the day. Also the magnetic field shows strong fluctuations. In the corona, within the bright volume the first «sporadic condensations» with loops in H_α and $\lambda 5303$ are seen. Again and again for some hours appear spot prominences on the sun's limb. Probably in the same region photospheric loops and flares occur.

6th to 13th day: The number of flares and flare surges per day as well as the brightness of the faculae close to the spots and of the corona in $\lambda 5303$ and in white light steadily increase. Violent condensations and motions are seen in the corona (H_α , $\lambda 5303$, $\lambda 5694$ and continuum). Several filaments are formed and dissolved again. The area of the B.M. region is still increasing, it is covered all over with the chromospheric threads (as seen in the center of H_α) which altogether form the well-known vortex structure of a C.A. In certain regions the threads appear in the form of large numbers of tightly packed loops.

14th to 30th day: The flare activity is decreasing. The spots are going to disappear, except the western main spot. The K -faculae has become very large indimensions and is still bright as compared to the K -network. The H_α -facula is already shrinking in size. Within the K -facular region a filament has become stable on the poleward side of the spot group. It is pointing toward the remaining spot and has a length of about 50 000 km. The corona is still bright in $\lambda 5303$, in integrated light it is fading. The B.M. region shows its largest magnetic flux.

30th to 60th day: The brightness of the H_α - and K -faculae is decreasing. The last spot disappears slowly. The remaining filament grows steadily in length (about 10^5 km/rotation) and swings into the direction of the parallels, dividing the faculae region into two halves with a dark corridor in between. While the filament is still bordered by chromospheric thread structures, the C.A. as a whole is continuously loosing its structures. Imperceptibly it is merging into the structures of a neighbouring C.A. Its diameter has grown to more than 150 000 km. The magnetic field in this region is still detectable but shows an irregular distribution.

60th to 100th day: The facular regions begins to dissolve. In H_α it has disappeared already, in K it resumes the form of a bright network. The disturbed magnetic field can still be observed. The prominence has reached its

maximum length and runs almost parallel to the equator and is still surrounded by thread structures and separates the B.M. region into two halves of opposite polarity.

100th to 200th day: The filament can reach a life-time of 100 to 250 days. Its disintegration probably occurs simultaneously with that of the B.M. region, the observable life-time of which is of the same order.

5. – Physical synopsis of the individual phenomena.

Many efforts have been made to interpret the great variety of phenomena occurring in a C.A. In the frame of this short paper we can try only to collect the basic physical ideas, which seem to be essential for understanding the physical mechanism which produces a C.A.

From the life story of a C.A. it can be seen quite clearly, that photosphere, chromosphere and corona form together a dynamic unity. We will see, that the primary event, which is practically alone responsible for the development of the different phenomena in the different layers is a magnetic disturbance, which comes from the interior of the sun and which penetrates photosphere and chromosphere to get into the corona.

Before we come to a physical model we will try to give a survey in very condensed form of the physics of sunspots, flares, surges, prominences and faculae as they are known today.

Theory of sunspots. – First we have to get acquainted with some unexpected properties of solar magnetic fields, which have a decisive influence on the structure of a C.A. The electric conductivity of the solar interior and of the sun's atmosphere being very high, the diffusion of a magnetic field across the lines of force will be extremely slow, only a small fraction of a mm/s [17]. The field is «frozen» into the matter. If the field is large enough ($H^2/8\pi > \epsilon v^2/2$, ρ and v density and velocity of material), then matter can move relative to the field only along the lines of force. The appearance of a magnetic field on the solar surface and its penetration into the solar atmosphere must be a phenomenon quite different from the penetration of a field into vacuum. It will be accompanied by mass motions [4].

It can be further easily shown, that the life-time of such a frozen in magnetic field is very great. With a conductivity of $\sigma = 10^{-4}$ e.m.u., a diameter of the magnetic field of $a = 1000$ km a life-time $t \sim 4\pi\sigma a^2 \sim 10^6$ years follows. One has to assume therefore, that the field of a sunspot, which is visible to us only for a few days, or that of a B.M. region existed already before in the interior of the sun and has been transported to the solar surface by convection.

In connection with the theory of sunspots E. N. PARKER [18] has shown, that a horizontal subphotospheric magnetic flux tube, which might be part of an interior toroidal field can be lifted to the surface by magnetic buoyancy. Such a flux tube, with a magnetic field H along its axis will have a smaller mass density than the surroundings, because—for the sake of equilibrium—the gas pressure in the interior plus magnetic pressure have to balance the gas pressure from the outside. The resulting difference in density results in a buoyancy force per cm length of the flux tube, which might have the cross-section A

$$g_{\odot}(\varrho_e - \varrho_i)A,$$

where ϱ_e and ϱ_i are the external and internal densities. Against this lifting force is acting the magnetic stress along the tube, which we assume to be fixed at its ends

$$AH^2/4\pi.$$

Only if the lifting force acting on the whole tube will exceed the stress in the tube it will start to rise and to become stretched. It will reach regions of diminishing density. The excess density in the rising tube however will glide back along the lines of force. With the penetration of this flux tube through the photosphere a bipolar magnetic region (B.M. region) will appear, which will grow according to the shape and velocity of the tube.

Within the magnetized region of the photosphere the convection of the gas is seriously hampered by the magnetic field and by this also the stream of energy coming from the interior.

The photosphere is cooled from about 6000° down to 4500° , the temperature observed in the umbrae of sunspots. This lower temperature leads—in order to maintain equilibrium between the interior and the outside of the flux tube—to a strong contraction of the tube and consequently to an increase of the magnetic field

from some 50 gauss up to several 1 000 gauss. This is roughly the mechanism which gives rise to the formation of a sunspot or of a bipolar sunspot group, which is illustrated in fig. 18. It is clear, that in this model the magnetic field is the primary cause, the cooling of the spots a consequence of it. Further details cannot be given here.

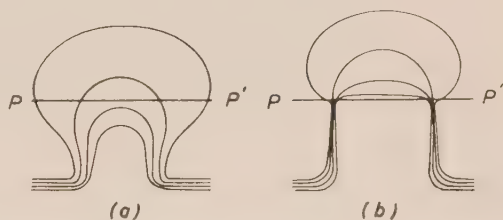


Fig. 18. - Parker's theory of the formation of a sunspot group.

Magnetic fields outside sunspots. - Until here it was assumed that the rising flux tube could pass the photospheric granulation without disturbance. The

average kinetic energy in the granulation is of the order of 100 erg/cm^3 . When putting the field energy $H^2/8\pi = \rho v^2/2$ the kinetic energy thus corresponds to a field of about 50 gauss. For fields ≤ 50 gauss one should expect therefore, that the granulation will not be affected by the field, but that the penetrating field will be shaped by the cellular convection in and between the granules. The field obviously can get out into the chromosphere only in the form of cells or flux tubes, the diameter of which cannot exceed the diameter of the granules ($\sim 750 \text{ km}$). One has to imagine, that the ascending magnetic field will be, so to say, threaded into the granulation and then be sluiced to the surface in thin threads.

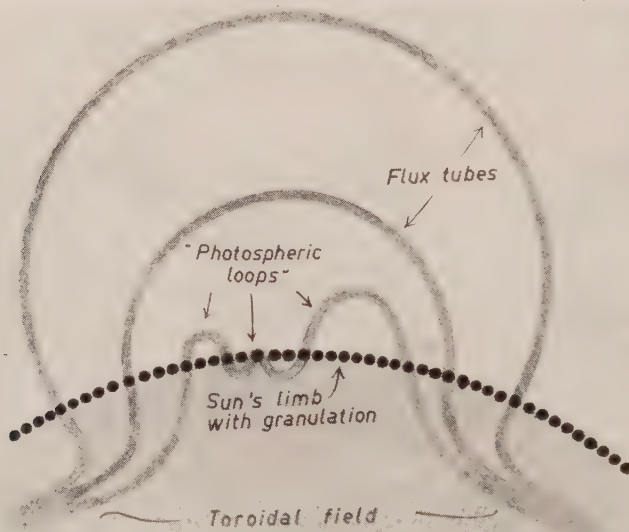


Fig. 19. — Emergence of a magnetic field in the form of looped flux tubes.

The magnetic stress in such a thread is $AH^2/4\pi$. This force will keep together the thread, as long as it is greater or of the same order as the gas pressure or the convective pressure outside. Consequently the threads in spite of being squeezed and stretched will not be torn, but come out of the granulation in the form of loops and slings as seen in Fig. 19. It can be assumed that the loops as observed in integrated light in the photosphere and in H_α in the chromosphere in the vicinity of sunspots are identical with these flux tubes. Their dimensions as well as the place where they are seen corresponds exactly to what one would expect [4].

One has to note further, that a difference of height of 1000 km in the solar atmosphere will be fallen through in a time of 90 s, falling along an inclination of 60° in 360 s, of 80° in 2000 s and 85° relative to the vertical

in 12 000 s. This means, that a flux tube, filled with photospheric matter, should be visible easily for a time of the order of an hour. Also the long lifetime of chromospheric threads and loops, which obviously run almost parallel to the sun's surface can be understood by means of this picture.

With the penetration of the flux tubes into the corona, they become invisible in general, however sometimes also in the corona slowly rising loops are observed in $\lambda 5303$, which could be the remainders of H_{α} -loops seen before in the chromosphere. Also in the corona the flow down of material in the flux tubes takes time. The average density of the corona over an active C.A. with a growing magnetic field will therefore exceed the density of an undisturbed region in the corona. Waldmeier's permanent coronal condensation can be explained in this way as a simple consequence of the field changes observed in sunspots and the associated B.M. region.

Has one to conclude from this mechanism of field penetration, that the magnetic field in the corona will only occur in the form of such loops? The form of prominence streamers as seen on the limb favours fields of much simpler shape, more of the type one would expect in vacuo above a sunspot group. One must assume therefore, that these loops merge together and are stretched in such a way, that a more homogeneous field results. This process of rectification, of linking up field lines is probably of the same type as DUNGEY and SWEET [19] have proposed for flares. In this case however the change of field does not produce any observable optical effects. Because of the smaller fields and densities involved here as compared to the flares, the effects might be confined to emission of radiation in the centimeter- and meter-wave band.

Theory of flares and flare surges. — The theory of flares as given by DUNGEY and SWEET [19] is based on a proposal of GIOVANELLI [20] made already in 1947. The authors assume, that two systems of magnetic field, which might originate in two bipolar pairs of spots «collide» in the inner corona because of two spot pairs having approached each other. The two coronal volumes of gas containing the magnetic fields cannot interpenetrate, because of the interaction of electric currents. They will be pressed together. Field and density will be squeezed together considerably into a collision layer. The densification of the field and also of the electric current producing it will be strongest in a magnetic neutral region, a point or a line, where the field passes through zero and changes sign.

The electric current will be pressed into such a thin layer, that the electrons have to reach almost the velocity of light, in order to produce the steep slope of the magnetic field. The Joule heat of this current will be sufficient to cover the emission of a flare and this in spite of the fact that the primary volume involved in this process is extremely small. It is not yet quite clear in which

form this energy released in a small region is transferred to the larger volume of the flare, as we see it in our telescopes.

Simultaneously with the current density also coronal matter will be densified, in such a way that magnetic pressure and gas pressure balance each other. This equilibrium is a dynamical one, because the squeezed material can escape from the collision region along the lines of force. In connection with such field collisions large coronal streams of matter can be put in motion.

The sudden densification of coronal matter, as one has to expect it especially in the vicinity of sunspots, has an interesting consequence which has to be discussed here, because of its importance for the production of flare surges and prominences [13-14]. The thermal equilibrium of the corona is mainly defined by the supply of mechanic energy (sound) and the loss of energy by radiation (free-free and free-bound transitions). This radiation is $\sim n_e^2$ and would cool a volume of the inner corona within a few hours from 10^6 to 10^4 degrees, if the energy supply is stopped. If an external (constant) pressure p_0 is applied on this volume by putting it in a cylinder (transparent for all radiations!) with a piston, the cooling will proceed much faster: if the temperature begins to decrease because of radiation cooling, the gas pressure of the enclosed volume will also go down. For conserving the equilibrium with the outside pressure p_0 , the gas will densify. With increasing density the radiation losses will increase $\sim n_e^2$. The result is, that the temperature will drop much faster, or in other words: In spite of compression, the pressure in the coronal material will not increase. It behaves like a vapour with a liquid phase, the pressure of which is independent of its volume.

The energy balance of this volume is (total energy content W , total number of electrons N)

$$\frac{dW}{dt} = \frac{3}{2} Nk \frac{dT}{dt} = -\frac{N}{n_e} n_e^2 f(T) + \frac{N}{n_e} n_e \varepsilon,$$

where $n_e^2 f(T)$ is the ergiebigkeit of the free-free and free-bound transitions,

$$f(T) = 5.44 \cdot 10^{-22} / \sqrt{T} + 1.44 \cdot 10^{-27} \sqrt{T}$$

and $n_e \varepsilon$ the energy supply to the corona per cm^3 and s.

The integration gives the course of temperature for an external pressure p

$$T - T_0 \left[1 - \alpha \left(\frac{p}{n_0 k T_0} - 1 \right) t \right],$$

where $\alpha = 2f_0 n_0 / 3k T_0$. If one puts, as to be expected in a C.A., $n_0 = 5 \cdot 10^9 \text{ cm}^{-3}$, $T = 10^6$ degrees, $\alpha = 7 \cdot 10^{-5}$ results. For an external pressure $p/(n_0 k T_0) \approx 2$ results a cooling time of 2 hours for obtaining half the tem-

perature. This pressure corresponds to a field of only 0.5 gauss. For a pressure corresponding to a field of 5 gauss the cooling time would be reduced to a few minutes.

This shows that coronal matter under the influence of variable magnetic fields can cool locally so much, that H_α -emission will begin. We must conclude that the so-called sporadic condensation (loop prominences etc.) occurring over C.A.'s are formed by such a cooling mechanism. Also flare surges might have a similar origin. In surges the coronal matter is not only cooled to a temperature of $\sim 10^4$ degrees but also—simultaneously—squeezed out along the lines of force by the pressure of the colliding fields («squeezatron»). As GIOVANELLI [13] has shown, the ejection of a surge can start already before its temperature will be low enough to give rise to H_α -emission or absorption. This observation suggests strongly that the surge does not originate in the chromosphere, is not made of chromospheric matter, but is condensed in the corona from coronal matter. Also for the flare itself this might be true in some cases, where the flare obviously occurred in the inner corona, detached from the sun's limb.

Prominences. — No comprehensive theory of prominences is available. The theory of KIPPENHAHN and SCHLÜTER [21] concerns only the problem of support in a magnetic field, without taking into account the characteristic motions and forms. Other investigations are confined only to the motions or the formation of prominences, others to their thermodynamics. There is no time to report here all these aspects. Here only this: There can be no doubt, that *all* prominences, whether in the vicinity of sunspots or far away in high latitudes, are related intimately to photospheric magnetic fields. They define their form and they screen them against the heavy bombardment of coronal ions. Only by this protection a prominence can survive as a cool body imbedded in the much hotter corona.

The first formation of a prominence in a C.A. occurs certainly with the assistance of a magnetic field, probably by condensation of coronal material. Also the stable, slowly growing filaments are always bordered by longitudinal magnetic fields of opposite polarity, and as one can see in the wings of H_α , they are always situated in a corridor without spicules. During the life-time of the associated faculae this corridor forms a dark lane dividing the facular area in two halves. The numerous threads which—as seen in projection on the disk—run from the chromosphere into the filament, end in the dark structures which border this corridor like a hedgerow.

From all this—the missing spicules under the filament and the dark lane in the faculae—it must be concluded, that the magnetic flux between the two halves of an older B.M. region is carried mostly by the threads connecting chromosphere and filament, which also here seem to function as magnetic flux tubes.

The motion of prominences (eruptive ascensions or sudden dissolution of a stable filament by streaming down into the chromosphere) can be explained only by sudden changes of the magnetic field, because every change of magnetic configuration will not only displace the filament but also disturb its mechanical equilibrium.

The activation of filaments also might be produced by shock waves or by hydromagnetic waves. The simultaneous occurrence of flares [10] in different C.A.'s shows that flares sometimes must be the sources of intense perturbations which travel with a velocity of about 1000 km/s and which are certainly strong enough to disturb the equilibrium of filaments.

Faculae. — Also the theory of faculae is still in an experimental state. As energy source for the heating of facular structures variable magnetic fields [22] and shock- resp. hydromagnetic waves [22] have been proposed.

The bright K - and H_{λ} -mottles, probably also the facular granules seen in integrated light, are produced probably by the spicules. The spicules probably occur only in regions of a radial magnetic field. The brightness of the mottles increases strongly in the C.A.'s. It must be assumed therefore that the magnetic field is of importance for the exciting mechanism. The energy required for this type of faculae however might be supplied by the spicule in the form of a shock wave.

As PIDDINGTON [23] has shown, the Joule heat of a hydromagnetic wave is negligible as compared to the energy dissipated by the friction between the oscillating ionized plasma and the neutral atoms, these atoms being forced by collisions with ions to take part in the oscillation. The largest effect is to be expected, where the density of the ions and that of the neutral particles is of the same order.

The Piddington mechanism can be applied very well to the bright H_{λ} - and K -mottles. It is still an open question whether it holds also for the much brighter H_{λ} -strands and K -flocculi near sunspots. Brightness and dimension of this type of faculae are so closely related to the strength and to the shape of the magnetic fields, the phenomenon as such looking so different, that one is tempted to think of another mechanism, which possibly is based exclusively—without contribution of hydromagnetic waves—on the effect of slowly variable strong magnetic fields. This must be also so, because there seem to occur no spicules in the very vicinity of sunspots or at least certainly not more frequently than in undisturbed regions of the solar surface.

A precise photometry of these bright regions would help to clear up this problem, because it could be decided then, whether the brightness is correlated more with the magnetic flux density or with its variation with time.

6. — Physical synthesis of a C.A.

A part of the toroidal field in the interior of the sun becomes detached and is lifted toward the photosphere by magnetic buoyancy. The lifted magnetic flux appears as a bipolar magnetic region (probably first along the network formed by the spicules) and is clearly marked by the brightening of H_{α} - and K -mottles. The magnetic field then contracts partially into sunspots where it becomes strong enough to hamper convection and to reduce the temperature of the visible photospheric layers down to 4500° .

Outside the spots the field energy ($H^2/8\pi$) is comparable with or smaller than the kinetic energy ($\rho v^2/2$) in the granulation layer. Here the granulation will distort the field, which can penetrate only in the form of granular portions or flux tubes of granular diameter, which obviously should be identified with the loops observed in photosphere, chromosphere and corona. The material lifted with these loops will glide down along the lines of force. In this way the loop density will stay roughly adapted to that of the surroundings. In regions where the field penetrates slowly enough the loops will be transformed gradually into threads connecting regions of photospheric longitudinal fields of opposite polarity.

The penetration of the field into the corona in the form of flux tubes will increase its electron density, because the lifted material will not be able to return to the sun without delay (mainly because of small inclination of the flux tubes and because of friction). The slowly expanding coronal arches probably represent the visible traces of this field propagation.

The collision of such portions of field in the corona, especially of fields originating in moving or rapidly developing sunspots will lead in neutral points or along neutral lines of the field to a high concentration of electric current density, such that Joule heat and densification of matter become considerable. A flare will occur. The energy transferred by the field to the collision layer will be used partly to cover the radiation losses of the flare, partly to compress and to set into motion, that is to squeeze out, coronal matter between the two colliding fields. A flare surge is formed, possibly consisting only of coronal matter, cooled down to about $10\,000^{\circ}$ by radiation and accelerated to speeds of the order of 100 km/s.

The simultaneous occurrence of $\lambda\,5694$ emission close to flares and spot prominences is another consequence of this concentration of electric current density, in which some electrons will easily obtain energies up to some MeV.

The formation of a stable filament which survives all the other phenomena of a C.A. is also intimately connected with the shape and the flux of the underlying B.M. region. It forms the coronal bridge which carries the magnetic flux connecting the two halves of the B.M. region, mostly by flux tubes in the

form of thread-shaped loops. The sudden disappearance of filaments can be understood then in terms of a transient perturbation of the magnetic field in the B.M. region, the duration of which cannot be much longer than a few hours or a day. This perturbation will produce a system of induction currents in the corona, which will be blown away by the Lorentz force and will take the filament with it or will disturb its equilibrium, so that it will glide down to the chromosphere.

The same perturbation of the magnetic field also is responsible for the occurrence of the flarelike brightenings along the base of the lifted filament thus showing us in a short time the mechanism, which might happen in the long lived H_x - and K -faculae which appear close to sunspots and which are so closely connected with the spots' magnetic field.

Going one step further in simplifying this already condensed synoptic picture of a C.A., one could say, that all the observed phenomena as faculae, sunspots, loops in all layers, flares, flare surges, prominences, coronal emissions and motions are direct products of a magnetic disturbance which has reached the solar surface. So we should better say: A center of activity is a magnetic storm in the solar atmosphere producing enormous changes of temperature, pressure and density as well as violent motions in all layers of the solar atmosphere, altogether a violent thunderstorm of a few weeks duration.

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Electromagnetic Theory of Antennas and Transmission Lines.

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I. — Basic Electromagnetic Theory.

The rationalized M.K.S. system of units will be used (see for instance, G. TORALDO DI FRANCIA: *Electromagnetic Waves* (1956)). In this system the velocity of light is

$$c = 2.998 \cdot 10^8 \simeq 3 \cdot 10^8 \text{ m/s},$$

the dielectric constant of free space is

$$(1) \quad \epsilon_0 = \frac{10^7}{4\pi c^2} = 8.854 \cdot 10^{-12} \text{ F/m}$$

and the magnetic permeability of free space is

$$(2) \quad \mu_0 = 4\pi \cdot 10^{-7} = 1.257 \cdot 10^{-6} \text{ H/m}.$$

1. — Maxwell's equations.

The magnetomotive force acting around a closed circuit is given by

$$U = \oint \mathbf{H} \cdot d\mathbf{l}$$

whilst the electromotive force is

$$V = \oint \mathbf{E} \cdot d\mathbf{l},$$

Maxwell's equations may be written in the integral form:

$$(3) \quad \mathcal{U} = I \quad \text{ampere}$$

and

$$(4) \quad V = -K \quad \text{volt},$$

where I is the total electric current linking the circuit (including any displacement current) and K the magnetic displacement current across the circuit (equal to $\partial\varphi/\partial t$, where φ is flux).

In Fig. 1, let Σ represent any regular surface, which may or may not separate two different media. The electric and magnetic fields on either side of the boundary are $\mathbf{E}^+$, $\mathbf{H}^+$, $\mathbf{E}^-$, $\mathbf{H}^-$ respectively, whilst $\mathbf{n}$ is the unit normal vector. From 3 and 4 it can be shown that

$$(5) \quad \mathbf{n} \wedge (\mathbf{H}^+ - \mathbf{H}^-) = \iota,$$

$$(6) \quad \mathbf{n} \wedge (\mathbf{E}^+ - \mathbf{E}^-) = 0,$$

$$(7) \quad \mathbf{n} \cdot (\mathbf{D}^+ - \mathbf{D}^-) = \sigma,$$

$$(8) \quad \mathbf{n} \cdot (\mathbf{B}^+ - \mathbf{B}^-) = 0,$$

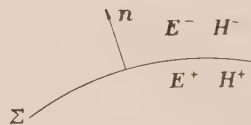


Fig. 1.

where ι represents the surface current density and σ the surface charge density.

If the fields are continuous and differentiable, Maxwell's equations may be written in the familiar form

$$(9) \quad \text{curl } \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} + \mathbf{J},$$

$$(10) \quad \text{curl } \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$

where $\mathbf{J}$ is the current density. Also the equation of continuity for the current density gives

$$(11) \quad \text{div } \mathbf{J} + \frac{\partial \rho}{\partial t} = 0,$$

where ρ is charge density. If the medium has conductivity γ there will be a conduction current given by

$$\mathbf{J} = \gamma \mathbf{E}.$$

If the medium is polarizable, and $\mathbf{P}$ is the polarization (electric dipole moment per unit volume), there will also be a polarization current

$$\mathbf{J} = \frac{\partial \mathbf{P}}{\partial t}$$

and a polarization charge density

$$\rho = -\operatorname{div} \mathbf{P}.$$

2. - Oscillating quantities.

Quantities oscillating at a prescribed frequency ω will be represented by expressions of the form $A \exp [i\omega t]$. The complex amplitude $A = A_0 \exp [i\varphi]$ represents both amplitude A_0 and phase angle φ . The factor $\exp [i\omega t]$ will be in general understood and not written down explicitly. Differentiation with respect to time may now be accomplished by multiplication by $i\omega$. Maxwell's equations (9), (10) now become

$$(12) \quad \operatorname{curl} \mathbf{H} = i\omega \varepsilon \mathbf{E} + \mathbf{J},$$

$$(13) \quad \operatorname{curl} \mathbf{E} = -i\omega \mu \mathbf{H}.$$

Any quantity which is the product of two such oscillating quantities can be obtained as a time average by multiplying one of them by the complex conjugate of the other, taking the real part and dividing by two. Thus Poynting's vector, representing the power density in the electromagnetic field, and usually written

$$\mathbf{S} = \mathbf{E} \wedge \mathbf{H},$$

becomes

$$S = \frac{1}{2} \operatorname{Re} \mathbf{E} \wedge \mathbf{H}^*$$

as the time-average of the power density.

3. - Impedance.

The ratio

$$Z = \frac{V}{I},$$

between electromotive force V and current I in any circuit is termed the impedance of that circuit. Furthermore, we may write

$$(14) \quad Z = R + iX,$$

where R is the resistance of the circuit and X the reactance.

The reciprocal

$$(15) \quad \frac{1}{Z} = Y = G + iB,$$

is called the admittance, where G is conductance and B susceptance.

Thus an inductance L presents a positive reactance or inductive impedance of $i\omega L$ whilst a capacitance C presents a negative reactance or capacitive impedance

$$\frac{1}{i\omega C} = -\frac{i}{\omega C}.$$

4. — The RLC circuit.

Consider the circuit of Fig. 2, in which resistance, inductance and capacitance are connected in series.

The total impedance will be

$$(16) \quad Z = R + i\omega L + \frac{1}{i\omega C}$$

and the admittance

$$(17) \quad Y = \frac{1}{R + i(\omega L - (1/\omega C))}.$$

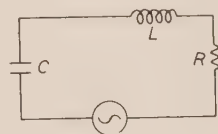


Fig. 2.

Resonance will occur when the reactance vanishes, at a frequency

$$(18) \quad \omega_0 = \frac{1}{\sqrt{LC}}.$$

At this frequency the current generated by a source of constant electromotive force will be a maximum. The average energy stored in the capacitance is found to be

$$(19) \quad U_c = \frac{1}{4} \frac{II^*}{\omega^2 C},$$

whilst that stored in the inductance is

$$(20) \quad U_L = \frac{1}{4} L I I^*,$$

here I is the current flowing. At resonance $\omega = \omega_0 = 1/\sqrt{LC}$ both stored energies are equal, and the total energy stored in the reactance is

$$(21) \quad U_x = \frac{1}{2} L I I^*.$$

Also the average power dissipated in the resistance is

$$(22) \quad W = \frac{1}{2} R I I^*.$$

One may now define a quantity Q such that

$$(23) \quad Q = \frac{\omega_0 U_x}{W} = 2\pi \frac{U_x}{WT},$$

where T is the period of the oscillation. Evidently

$$Q = 2\pi \times \left(\frac{\text{energy stored in reactance}}{\text{energy lost per cycle}} \right).$$

Also in the RLC circuit we have, by (21) and (22),

$$(24) \quad Q = \frac{\omega_0 L}{R}.$$

In the vicinity of resonance, we may write

$$(25) \quad \omega = \omega_0(1 + \delta) \quad \text{with } \delta \ll 1,$$

Equation (17) now becomes

$$(26) \quad Y = \frac{1}{R} \cdot \frac{1}{1 + 2iQ\delta},$$

whilst the power dissipated in the circuit is

$$(27) \quad W = \frac{1}{2} R Y V Y^* V^* = \frac{V V^*}{2R} \cdot \frac{1}{1 + 4Q^2\delta^2}$$

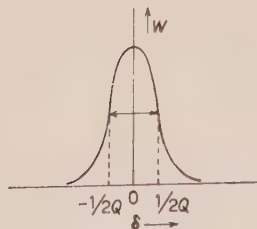


Fig. 3.

(remembering that $I = YV$). W is plotted in Fig. 3 as a function of δ .

The power W is maximum at resonance ($\delta = 0$) and falls off on either side. For $\delta = \pm 1/2Q$ the power has one half of its maximum value. Thus $1/Q$ represents the width of the response curve. A high Q means high selectivity, while a low Q gives a broad band circuit.

The oscillations in an RLC circuit are damped, the amplitude steadily decreasing with time. The Fourier analysis of such a damped wave-train yields a frequency spectrum which exactly reproduces the resonance curve.

5. — The two-wire transmission line.

Fig. 4 represents a two-wire transmission line, carrying power from a generator to a load impedance Z_L .

This system of two equal parallel wires is assumed to be infinitely far from any other conductor, and hence by symmetry the current $I(z)$ in the line at a given distance z from the generator will have equal and opposite values on each wire. The voltage $V(z)$ is defined as the electromotive force acting, from the lower towards the upper wire at the distance z from the generator.

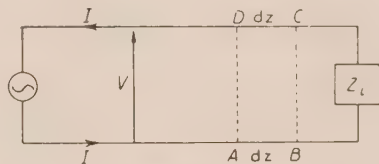


Fig. 4.

Consider the infinitesimal rectangle $ABCD$, with $AB = CD = dz$. Applying equation (4) to the circuit $ABCD$ we have

$$(28) \quad V(z + dz) - V(z) + \mathcal{R}I dz = -i\omega d\varphi,$$

where $d\varphi$ is the magnetic flux across the area $ABCD$ and $\frac{1}{2}\mathcal{R}$ is the resistance of each wire per unit length. But the flux is also

$$d\varphi = \mathcal{L}I dz,$$

where $\mathcal{L}$ is the inductance per unit length. Thus we may write (28) as

$$(29) \quad \frac{dV}{dz} = -\mathcal{Z}I$$

in which

$$(30) \quad \mathcal{Z} = \mathcal{R} + i\omega\mathcal{L}$$

has the dimensions of impedance per unit length (ohms per metre), and is termed the series impedance of the line.

The current will also vary along the line, as some will leak from one wire

to the other through the conductance of the dielectric between them, and the admittance of the capacitance between them. We may define a total admittance

$$(31) \quad \mathcal{Y} = \mathcal{G} + i\omega\mathcal{C},$$

where $\mathcal{Y}$ and $\mathcal{G}$ are measured in mho per metre, and $\mathcal{C}$ in farad per metre. For every element dz of the line, this shunt admittance will allow a current $\mathcal{Y}Vdz$ to leak across and be lost to the following section of the line. Thus we have

$$(32) \quad \frac{dI}{dz} = -\mathcal{Y}V.$$

Equations (29) and (32) are the fundamental equations of the two-wire line.

6. - Waves on a transmission line.

Equations (29) and (32) have the two independent solutions:

$$(33) \quad V(z) = V_p \exp[-hz], \quad I(z) = \frac{V(z)}{Z},$$

and

$$(34) \quad V(z) = V_r \exp[hz], \quad I(z) = -\frac{V(z)}{Z},$$

where V_p and V_r are (complex) constants of integration, whilst

$$(35) \quad h = \alpha + i\beta = \sqrt{\mathcal{Y}\mathcal{Z}}, \quad (\alpha \geq 0, \beta > 0),$$

and

$$(36) \quad Z = R + iX = \sqrt{\frac{\mathcal{Z}}{\mathcal{Y}}}, \quad (R \geq 0).$$

Solution (33) represents progressive waves, whilst (34) represents regressive waves. h is the propagation constant, α the attenuation constant, $\beta = 2\pi/\lambda$ the wave number and λ the wavelength along the line. The constant Z is termed the characteristic impedance of the line, and is the impedance presented to the generator when only progressive waves are present.

The phase velocity along the line is

$$(37) \quad v = \frac{\omega}{\beta}.$$

If $\mathcal{R} = \mathcal{G} = 0$ the line is lossless, and (35) and (36) become

$$(38) \quad \alpha = 0, \quad \beta = \omega \sqrt{\mathcal{L}\mathcal{C}},$$

$$(39) \quad Z = \sqrt{\frac{\mathcal{L}}{\mathcal{C}}}.$$

For two cylindrical wires of radius a surrounded by air and placed at a centre-to-centre distance b , with $b \gg a$, it can be shown that

$$\mathcal{L} = \frac{\mu_0}{\pi} \ln \frac{b}{a} \quad \text{and} \quad \mathcal{C} = \frac{\varepsilon_0 \pi}{\ln(b/a)}.$$

Thus $\beta = \omega \sqrt{\varepsilon_0 \mu_0}$, or, by (37), $v = c$, and

$$(40) \quad Z = \frac{1}{\pi} \sqrt{\frac{\mu_0}{\varepsilon_0}} \ln \frac{b}{a} = 120 \ln \frac{b}{a} \, \Omega.$$

In most practical applications Z is from 300 to 600 Ω .

II. — Impedance Matching.

Let us now take into account the load impedance Z_L , which, incidentally, could also be represented by another transmission line of characteristic impedance Z_L connected in series with our line of characteristic impedance Z . In general, the presence of Z_L makes it impossible to have only a progressive wave on the line. In addition to the progressive wave, a regressive wave is generated on reflection of the progressive wave at the load Z_L .

Without loss of generality we can put $z = 0$ at the position of the load. We thus have the condition

$$\frac{V(0)}{I(0)} = Z_L.$$

This, by (33) and (34), gives us

$$(41) \quad \frac{V_p(0) + V_r(0)}{I_p(0)/Z - I_r(0)/Z} = Z_L,$$

whence we derive the reflection coefficient

$$(42) \quad r = \frac{V_r}{V_p} = \frac{Z_L - Z}{Z_L + Z}.$$

We see that reflection can be avoided only by making $Z_L = Z$.

We now ask what will be the impedance appearing at the terminals AB situated on the line at a distance l from Z_L (see Fig. 5). On the line we have the superposition of the progressive and the reflected waves. The voltage and the current therefore are given by the following expressions:

$$(43) \quad V(z) = V_p \exp[-i\beta z] + \frac{Z_L - Z}{Z_L + Z} V_p \exp[i\beta z],$$

$$(44) \quad I(z) = \frac{V_p}{Z} \exp[-i\beta z] - \frac{Z_L - Z}{Z_L + Z} \frac{V_p}{Z} \exp[i\beta z],$$

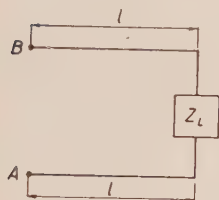


Fig. 5.

whence, by putting $z = -l$ we obtain

$$(45) \quad \frac{V(z)}{I(z)} = Z \frac{Z_L + iZ \operatorname{tg} \beta l}{Z + iZ_L \operatorname{tg} \beta l}.$$

This is the impedance which appears across AB . It varies with l and we can take advantage of this fact when it is desired to get a prescribed value of the impedance across AB . For instance, suppose we want a real impedance Z' to appear across AB . By putting $l = \lambda/4 = \pi/2\beta$, (45) yields

$$(46) \quad \frac{V(z)}{I(z)} = \frac{Z^2}{Z_L}.$$

This will be equal to Z' if we take

$$(47) \quad Z = \sqrt{Z' Z_L}.$$

In this way we can match, *i.e.* connect without reflection taking place, a line of characteristic impedance Z' to a line of characteristic impedance Z_L by inserting a $\lambda/4$ section of a line whose characteristic impedance Z is the geometric mean of Z' and Z_L .

As a matter of fact, this kind of matching is only feasible for one particular frequency. In order to broaden the band one can insert several sections of different lines between Z' and Z . In the limit one obtains a line whose characteristic impedance varies slowly from one value to another.

1. - Two-strip line.

As is well-known, a particular solution of Maxwell's equations (12) and (13) in a lossless homogeneous medium consists of a plane wave, which in rectangular co-ordinates can be represented as

$$(48) \quad E_x = E_0 \exp[-i\beta z],$$

$$(49) \quad H_y = \frac{E_0}{Z} \exp[-i\beta z],$$

$$(50) \quad E_y = E_z = H_x = H_z = 0,$$

where

$$(51) \quad \beta = \omega\sqrt{\varepsilon\mu},$$

$$(52) \quad Z = \sqrt{\frac{\mu}{\varepsilon}}.$$

Suppose now we limit the field by two metal plates parallel to yz (see Fig. 6).

If we suppose the plates to be perfect conductors and to be infinitely extended, the field (48), (49) can exist between the plates, while vanishing outside. In virtue of (5) and (7) there will appear a surface current

$$(53) \quad \mathbf{i} = \mathbf{i} \wedge \mathbf{H} = \frac{E_0}{Z} \exp[-i\beta z] \mathbf{k}$$

and a surface charge

$$(54) \quad \sigma = \mathbf{i} \cdot \mathbf{D} = \varepsilon E_0 \exp[-i\beta z]$$

on the lower plate and equal but opposite currents and charges on the upper plate.

If we mentally isolate on each plate a strip of width a equal to the spacing of the plates (Fig. 6) we have a current through the strips equal to

$$(55) \quad I(z) = \frac{E_0}{Z} \exp[-i\beta z] a,$$

with a voltage

$$(56) \quad V(z) = E_0 \exp[-i\beta z] a.$$

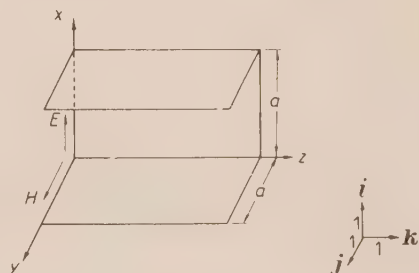


Fig. 6.

We thus are dealing with a two-strip transmission line with characteristic impedance Z . We conclude that a homogeneous medium is equivalent (as far as plane waves are concerned) to a set of two-strip transmission lines with square cross-section and of characteristic impedance $Z = \sqrt{\mu/\varepsilon}$. For this

reason we may assign an intrinsic impedance to the medium. In free space we have

$$(57) \quad Z = Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 120\pi = 377 \, \Omega,$$

whereas, of course,

$$\beta = \beta_0 = \omega \sqrt{\epsilon_0 \mu_0} = \omega/c.$$

The treatment of a homogeneous medium as a transmission line proves advantageous in many cases. For instance, if a plane wave impinges with normal incidence on a plane surface separating two dielectrics of intrinsic impedance Z and Z' , one immediately obtains from (42) the reflection coefficient

$$\frac{Z' - Z}{Z' + Z}.$$

In this connection E behaves like V and H like I .

2. - Coaxial cable.

Another kind of transmission line which we shall briefly discuss is the coaxial cable, represented in Fig. 7. One of the conductors is the inner cylinder, of radius a and the other conductor is the outer cylinder of radius b . Let us assume that the field has axial symmetry and that E is purely radial.

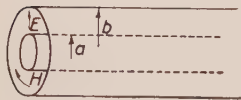


Fig. 7.

On applying (3) it is easily seen that H is purely tangential and that it is given by

$$(58) \quad H = \frac{I}{2\pi r},$$

where I is the current through the inner conductor.

In virtue of (5) and (58) the surface current on the inner conductor equals $I/2\pi a$ while the surface current on the outer conductor is $-I/2\pi b$. As a consequence, the total current through the outer conductor equals $-I$, i.e. is equal and opposite to that through the inner conductor.

Let us suppose that

$$(59) \quad I(z) = I(0) \exp[-i\beta z].$$

The equation of continuity, applied to our case, requires a surface charge to appear on the inner conductor given by

$$(60) \quad \sigma = -\frac{1}{i\omega} \frac{d(I/2\pi a)}{dz} = \frac{\beta}{\omega} \frac{I_0}{2\pi a} \exp[-i\beta z].$$

There is thus a charge $(\beta/\omega)I_0 \exp[-i\beta z]$ on a unit length of the inner conductor. Consequently, applying Gauss' theorem, we find

$$(61) \quad E = \frac{\beta}{\omega\epsilon} \frac{I_0}{2\pi r} \exp[-i\beta z].$$

Hence the voltage between the conductors is found to be

$$V = \int_a^b E dz = \frac{\beta I_0}{2\pi\epsilon\omega} \ln \frac{b}{a} \exp[-i\beta z]$$

and the characteristic impedance

$$(62) \quad Z = \frac{V}{I} = \frac{\beta}{2\pi\epsilon\omega} \ln \frac{b}{a}.$$

If the medium between the conductors is assumed to be air, then, on substituting (58) and (61) into Maxwell's equations, one finds $\beta = \omega\sqrt{\epsilon_0\mu_0}$ and (62) becomes

$$(63) \quad Z = \frac{Z_0}{2\pi} \ln \frac{b}{a} \simeq 60 \ln \frac{b}{a}.$$

We thus find that the characteristic impedance of a coaxial cable in practical cases is about 60 Ω . The phase velocity of the wave equals c .

3. - Wave guides.

The two wire line, the two strip line and the coaxial cable are only three particular cases of structures which can sustain guided waves. Power transmission can be treated either by considering V and I , thus centering attention upon the conductors, or by considering $\mathbf{E}$ and $\mathbf{H}$ whereby attention is given to the dielectric. Both procedures are correct and give the right results.

In the three cases considered both $\mathbf{E}$ and $\mathbf{H}$ are perpendicular to the direction of propagation. Accordingly, the field is said to be transverse electro-

magnetic, or TEM. Head-on views of these three cases are shown by Fig. 8. Solid lines represent the E -lines, broken lines the H -lines.

Guided waves can also travel in modes where either E or H has a non-vanishing longitudinal component. These are called transverse magnetic (TM) and transverse electric (TE) modes. Whereas the phase velocity of a



Fig. 8.

TEM mode equals the velocity of light in the dielectric, the phase velocity of a TE or TM mode is always greater than the velocity of light. If a waveguide can sustain both the TEM and other modes, the TEM mode is named the principal mode.

However, there are cases where the waveguide cannot sustain a TEM mode. This happens when the cross-section of the waveguide is a closed curve and

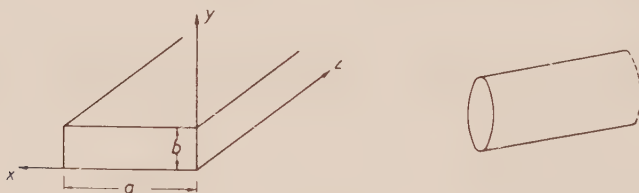


Fig. 9.

if the portion of the plane bounded by this curve is simply connected. Very important special cases are the rectangular and the circular waveguides (Fig. 9).

The rectangular waveguide can propagate a TE mode of the form

$$(64) \quad E_x = E_z = 0, \quad E_y = E_0 \sin\left(\pi \frac{x}{a}\right) \exp[-i\beta_g z],$$

$$(65) \quad \begin{cases} H_x = \frac{E_0}{Z_0} \left(1 - \frac{\lambda_0^2}{4a^2}\right)^{\frac{1}{2}} \sin\left(\pi \frac{x}{a}\right) \exp[-i\beta_g z], & H_y = 0, \\ H_z = -i \frac{E_0}{Z_0} \frac{\lambda_0}{2a} \cos\left(\pi \frac{x}{a}\right) \exp[-i\beta_g z], \end{cases}$$

where the wavenumber in the guide is given by

$$(66) \quad \beta_g = \beta \sqrt{1 - \frac{\lambda_0^2}{4a^2}},$$

so that the phase velocity turns out to be

$$(67) \quad V = \frac{c}{(1 - \lambda_0^2/4a^2)^{\frac{1}{2}}}.$$

This mode, which is called TE_{10} , can travel in the waveguide provided that $a > \lambda_0/2$. If $\lambda_0 > a > \lambda_0/2$ and $b < \lambda_0/2$ this mode is the only one which can travel in the waveguide; it is called the dominant mode.

In this case it is not so obvious as in the previous cases how one should define a voltage, a current and a characteristic impedance. However, by adopting some reasonable conventions most of the concepts introduced for transmission lines can be applied to a waveguide.

4. - Resonant circuits with distributed constants.

We consider again a lossless two-wire line which now is short-circuited at $z=0$ (see Fig. 10). This means that in eq. (43) and (44) we must put $Z_L=0$. This leads to

$$(68) \quad V(z) = -2iV_p \sin \beta z,$$

$$(69) \quad I(z) = 2 \frac{V_p}{Z} \cos \beta z.$$

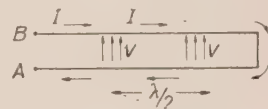


Fig. 10.

We now have obtained stationary waves. The nodes of the voltage coincide with the antinodes of the current and vice-versa. The spacing between two adjacent nodes or antinodes is half a wavelength.

If the line has a length l , the impedance appearing across AB will be

$$(70) \quad \begin{aligned} V(-l) \\ I(-l) \end{aligned} = iZ \operatorname{tg} \beta l$$

i.e. a pure reactance.

If we increase the line length, starting from $l=0$, the impedance is first inductive (positive reactance), goes to infinity for $l = \lambda/4$, then becomes capacitive (negative impedance) and goes to zero for $l = \lambda/2$. The same cycle is repeated every half wavelength.

If the line is open at the end ($Z_L = \infty$) we get

$$(71) \quad \begin{cases} V(z) = 2V_p \cos \beta z, \\ I(z) = -2i \frac{V_p}{Z} \sin \beta z. \end{cases}$$

This is again a standing wave, but in this case the nodes and anti-nodes of the voltage are interchanged with those of the current (see Fig. 11). The impedance at AB is now

$$(73) \quad \frac{V(-l)}{I(-l)} = -iZ \operatorname{ctg} \beta l.$$

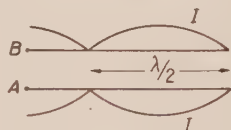


Fig. 11.

It is infinite for $l = 0$, becomes a capacitive reactance for $0 < l < \lambda/4$, vanishes for $l = \lambda/4$, then becomes an inductive reactance for $\lambda/4 < l < \lambda/2$, and so on.

If the generator is located in the vicinity of a node of the voltage, it obviously will supply a large current even though the voltage is only small. If the generator is located exactly at a voltage node, no voltage will be required from it at all. In this case we can simply dispense with the generator and short circuit the line at the location of the generator. The stationary waves will go on indefinitely by themselves, and the line has turned into a resonance circuit.

The condition of resonance for a line short-circuited at both ends is that

$$(74) \quad l = n \frac{\lambda}{2}.$$

If l is fixed, resonance can be achieved by varying the frequency. Since we have $\omega = 2\pi v/\lambda$, we have the condition

$$(75) \quad \omega_n = n\pi \frac{v}{\lambda}.$$

There is an infinity of resonance frequencies, all multiples of the fundamental frequency $\omega_1 = \pi v/\lambda$. To each frequency corresponds a particular mode of oscillation.

The system considered is a circuit with distributed constants. It behaves like an infinite set of resonant circuits with lumped constants (simple LC circuits) connected in parallel. The analogy still holds if the losses in the line are taken into account. It is possible to define a Q_n for each resonance fre-

quency ω_n , so that for the n -th mode the circuit behaves like a resonant RLC circuit with $Q = Q_n$. It turns out that

$$(76) \quad \frac{1}{Q_n} = \frac{1}{Q'_n} + \frac{1}{Q''_n},$$

where

$$(77) \quad Q'_n = \frac{\omega_n \mathcal{L}}{\mathcal{R}} \quad \text{and} \quad Q''_n = \frac{\omega_n \mathcal{C}}{\mathcal{G}},$$

corresponding to the two different types of losses in the line.

5. - Resonant cavities.

We have seen that the two-wire transmission line is just a special case of a transmission line or of a waveguide. The same is true for the resonant structure treated in the preceding section. A rectangular waveguide short-circuited at both ends (Fig. 12) is also a resonant structure. The resonant

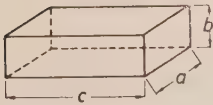


Fig. 12.

frequencies are those for which the length a of the waveguide is a multiple of half the wavelength λ_g in the waveguide. As a matter of fact, Fig. 12 represents nothing but a rectangular cavity. We thus may say that a rectangular cavity behaves like a circuit with distributed constants. If the left end of the cavity is open one may speak of the input impedance to the cavity, *i.e.* the impedance which the cavity presents to a waveguide of the same cross-section, carrying energy to the cavity. If $c < \lambda_g/4$ the impedance is inductive, if $\lambda_g/4 < c < \lambda_g/2$ it is capacitive, and so on.

Generalizing still further one may consider a cavity of any shape with a waveguide carrying energy into it (see Fig. 13). Energy may be dissipated in the cavity either at the walls of it, or because of any absorbing material contained in it. Some energy is reflected and standing waves may be generated in the waveguide. The cavity will be said to have an input impedance at AB equal to that particular impedance Z , which would give rise to the same type of standing waves in a two-wire line.

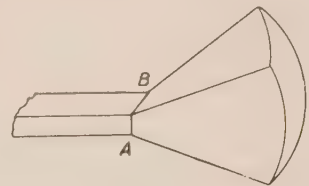


Fig. 13.

The Q of the cavity for the mode considered is defined as 2π times the ratio between the energy stored and the energy dissipated per cycle. It is related to the width of the resonance band.

If we want the maximum amount of power to be transferred from the guide into the cavity, we shall have to match the waveguide to the cavity. For instance we may use a waveguide with a characteristic impedance equal to the input impedance of the cavity. Since the characteristic impedance of the waveguide is practically real, the same will be true of the input impedance of the cavity, so the cavity must be at resonance. The higher the Q of the cavity, the more critical is the condition for resonance and the more narrow the band of frequencies for which the waveguide is matched to the cavity. If we want the matching to hold for a broad band, we must see to it that the energy stored in the cavity be small as compared to the energy dissipated.

III. - Dipole Radiation.

If a certain region V of a homogeneous dielectric contains an impressed density of electric polarization $\mathbf{P}$ in general variable from point to point, one can set up a Hertz vector $\mathbf{\Pi}$, which obeys the equation

$$(78) \quad \nabla^2 \mathbf{\Pi} + \beta^2 \mathbf{\Pi} = -\frac{1}{\varepsilon} \mathbf{P},$$

where β represents the wave number. It is a consequence of Maxwell's equations that the field outside V is represented by

$$(79) \quad \mathbf{E} = \text{curl curl } \mathbf{\Pi} = \text{grad div } \mathbf{\Pi} + \beta^2 \mathbf{\Pi},$$

$$(80) \quad \mathbf{H} = i\omega\varepsilon \text{ curl } \mathbf{\Pi}.$$

Eq. (78) has the well known solution

$$(81) \quad \mathbf{\Pi} = \int_V \mathbf{P} \frac{\exp[i\beta r]}{4\pi r} dv,$$

plus a solution of the homogeneous equation, where r represents the distance from dV to the point of observation. The right side of (81) represents the field radiated by the source $\mathbf{P}$. In the case of a point dipole $\mathbf{p}$ ($\mathbf{P} = \mathbf{p}$ times the Dirac function of space) one simply obtains

$$(82) \quad \mathbf{\Pi} = \mathbf{p} \frac{\exp[-i\beta r]}{4\pi\varepsilon r}$$

and from (79), (80),

$$(83) \quad \mathbf{E} = -\omega\beta Z \frac{\exp[-i\beta r]}{4\pi r} \mathbf{s} \wedge (\mathbf{s} \wedge \mathbf{p}) + O\left(\frac{1}{r^2}\right),$$

$$(84) \quad \mathbf{H} = \omega\beta \frac{\exp[-i\beta r]}{4\pi r} \mathbf{s} \wedge \mathbf{p} + O\left(\frac{1}{r^2}\right).$$

This is the radiation from an electric dipole. The far field, *i.e.* the field at a large distance, is represented only by the terms proportional to $1/r$. It is a spherical wave diverging from $\mathbf{p}$. The field vectors are tangent to the wave surface and are oriented as in Fig. 14.

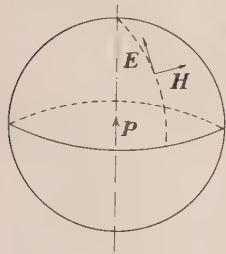


Fig. 14.

Radiation (Poynting's vector) is maximum at the equator and falls off to zero at the poles, *i.e.* in the direction of $\mathbf{p}$.

By integrating the Poynting vector over the entire sphere, one obtains the total power radiated by the dipole in free space:

$$(85) \quad W = 40\pi^2 \frac{\omega^2}{\lambda^2} p p^*.$$

1. - Passage from a terminated line to an antenna.

Let us consider a two-wire transmission line, terminated in open circuit (Fig. 15). We already know that when the line is energized, standing waves will appear, with a node of the current located at the termination. We also know that the current will have equal and opposite values at any pair of corresponding points like AB .

We recalled that a variable polarization $\mathbf{P}$ is equivalent to a current $\mathbf{J} = \partial\mathbf{P}/\partial t \rightarrow i\omega\mathbf{P}$. Conversely, we can picture any current $\mathbf{J}$ as a variable polarization $\mathbf{P} = \mathbf{J}/i\omega$. Thus any current element $I d\mathbf{l}$ on a wire is equivalent to a dipole

$$(86) \quad d\mathbf{k} = \frac{1}{i\omega} I d\mathbf{l}.$$

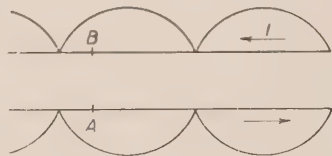


Fig. 15.

Hence, each element of the wires of Fig. 15 will emit dipole radiation. However since the dipoles at A and B are equal and opposite, their far field radiation will cancel. Thus the terminated line will not radiate.

Now, we saw that the characteristic impedance of the line depends on the ratio b/a , where a is the radius of each wire and b the axis-to-axis distance. If both a and b vary slowly along the line, always maintaining the same ratio

(Fig. 16) the characteristic impedance will stay constant and we shall have the same current distribution along the line. We note that now the radiation from A and B will not cancel. Indeed the longitudinal components of the

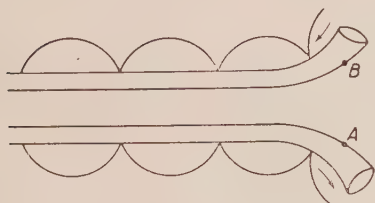


Fig. 16.



Fig. 17.

currents are equal and opposite, but the transverse components are simply equal.

The termination of the line has become an antenna.

The approximation made is extremely good in the case of Fig. 16. It is

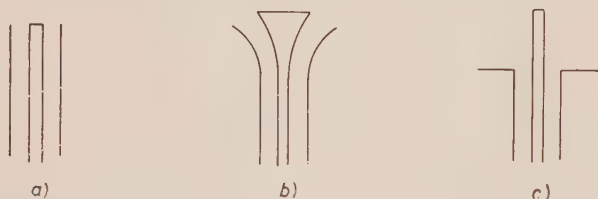


Fig. 18.

little worse, but still fairly good in the case of Fig. 17-a) and of Fig. 17-b). Thus we have gradually passed to the case of a linear antenna.

A similar gradual passage brings us from the coaxial cable to the stub

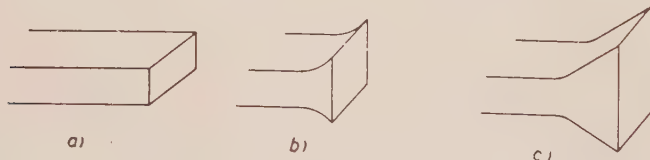


Fig. 19.

antenna on a ground plane as shown in Fig. 18-a), b), c), and from an open wave-guide to a horn antenna, as shown in Fig. 19-a), b), c).

From these examples it is clear that an antenna has the task of matching the impedance of the feeding line to the impedance of free space.

2. - The space as a cavity.

It is instructive to consider the space surrounding an antenna, as a cavity.

This is shown in Fig. 20 where the antenna is supposed to be located inside a cavity C . If the walls of C are sufficiently far from the antenna (in the far field zone) and are assumed to be coated inside with a perfectly absorbing layer it is evident that the cavity will not disturb the radiation of the antenna. The power which the antenna would radiate into free space becomes now the power dissipated inside the cavity.

If the line is matched to the antenna, the line will only entertain a progressive wave and the whole power carried by this wave will either be radiated or dissipated in the antenna itself. Alternatively, we may say that the line is matched to the cavity C , so that the cavity is in a state of resonance and its input impedance is a

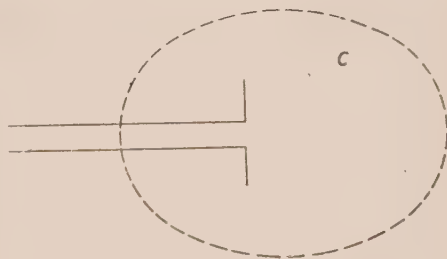


Fig. 20.

pure resistance, equal to the characteristic impedance of the line. But we know that resonance will only take place for a given frequency and that the resonance band-width is $1/Q$. On the other hand the Q of the cavity will obviously be given by 2π times the energy stored around the antenna divided by the energy radiated or dissipated in the antenna per cycle. Therefore, if we want the antenna to work properly for a broad band, we must see to it that the energy stored in the field around the antenna be small with respect to the energy radiated per cycle.

In practice the consideration of the cavity is dispensed with and one simply speaks of a resonant antenna and of the Q of the antenna.

3. - Radiation resistance.

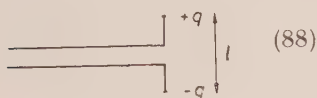
The antenna appears to the transmission line as an impedance $Z_A = R_A + iX_A$ and the power absorbed by the antenna will be $\frac{1}{2}R_A II^*$. This power will consist of the power dissipated in heat in the antenna, which will be put in the form $\frac{1}{2}R_d II^*$ plus the power radiated, which will be put in the form $\frac{1}{2}R_r II^*$. It is customary to term R_d the loss resistance and R_r the radiation resistance of the antenna.

We shall obviously have

$$(87) \quad R_A = R_r + R_d.$$

As an example let us evaluate the radiation resistance of a short dipole (Fig. 21) with uniform current.

If $+q$ and $-q$ are the charges on both ends respectively the moment will be $p = ql$ and the current $I = i\omega q$ so that $p = UI/i\omega$. By substituting this into (85), we obtain the power radiated



$$W = 40\pi^2 \frac{l^2}{\lambda^2} II^*$$

Fig. 21.

and consequently the radiation resistance

$$(89) \quad R_r = 80\pi^2 \frac{l^2}{\lambda^2}.$$

Strictly speaking, this expression holds only for $l \ll \lambda$. In this case the radiation resistance of the dipole is very small. However, if we try and make $l = \lambda/2$, we find $R_r = 197 \Omega$, a value not very different from 168Ω , which is found by a correct calculation for a $\lambda/2$ antenna with uniform current.

4. - Radiation patterns.

The radiation from an antenna is conveniently represented by its *radiation pattern*, which is built by taking an arbitrary origin and drawing in each direction a radius vector proportional to the far field values of E or H (field radiation patterns) or of the power (power radiation pattern) in that direction. For instance, Fig. 22 represents the power radiation pattern of a short dipole in the meridional plane ($\sin^2 \theta$ pattern). The entire pattern would have the shape of a doughnut.

Instead of the radiation pattern one can consider the *reception pattern*, which can be obtained as follows. When a plane wave impinges on the antenna, it induces a current across the terminals. For a given polarization of the impinging wave, this current becomes a maximum. The reception pattern will be constructed by drawing in each direction a vector proportional to the maximum current induced by a plane wave coming from that direction. The reception pattern constructed in this way corresponds to the field radiation pattern.



Fig. 22.

There is a general theorem of reciprocity for the electromagnetic field, which in our case can be worded as follows (see for instance, J. D. KRAUS: *Antennas* (New York, 1950), p. 252). If an e.m.f. is applied to the terminals of an antenna A and the current measured at the terminals of another

antenna B , then an equal current (in both amplitude and phase) will be obtained at the terminals of antenna A if the same e.m.f. is applied to the terminals of antenna B . It is assumed that the generator supplying the e.m.f. and the ammeter for measuring the current have equal impedance. A minute of reflection is sufficient to see that, as a consequence of this theorem, the radiation and reception patterns of an antenna are the same.

For this reason, in the sequel we will only speak of the radiation pattern.

It is sometimes of interest to consider an isotropic antenna, *i.e.* an antenna having a sphere as radiation pattern. Such an antenna is only ideal and cannot exist in reality. If an isotropic source radiates a total power W_r , its radiating intensity (*i.e.* power per unit solid angle) will be obviously given by

$$(90) \quad U = \frac{W_r}{4\pi}.$$

5. - Directivity.

In general, the radiation intensity $U(\theta, \varphi)$ of an antenna will be a function of direction. Let us assume that it presents a maximum U_m in a given direction. Then we shall define the *directivity* of the antenna as the ratio of U_m to the intensity of an isotropic antenna emitting the same total power. Therefore, indicating directivity by A , we shall have

$$(91) \quad A = \frac{U_m}{U_0} = \frac{4\pi U_m}{W_r}.$$

For instance, a short dipole has a radiation pattern $U = U_m \sin^2 \theta$, and since $\int \sin^2 \theta d\Omega = \frac{8}{3}\pi$, we obtain $W_r = \frac{8}{3}\pi U_m$ and $A = \frac{3}{2}$. Of course, an isotropic antenna has directivity $A = 1$.

If an ideal antenna could radiate constant intensity U_m through a small solid angle Ω and zero intensity outside Ω , its directivity would be

$$(92) \quad A = \frac{4\pi}{\Omega}.$$

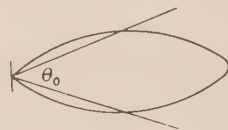


Fig. 23.

This ideal case is sometimes approached by antennae which have a sharp main lobe and very small (if any) side lobes. The value of Ω is then assessed by means of the half-power beam-widths (Fig. 23) of the main lobe in two planes at right angles. If θ_0, φ_0 are these two half-power beam-widths, one can put approximately $\Omega = \theta_0 \varphi_0$ and write

$$(93) \quad A = \frac{4\pi}{\theta_0 \varphi_0}.$$

If θ_0 and φ_0 are given in degrees this formula becomes approximately

$$(94) \quad \Delta = \frac{4}{\theta_0 \varphi_0} \cdot 10^4.$$

When the beam-width is small (a few degrees), this formula gives sufficiently accurate results.

6. - Gain.

When there are losses in the antenna, it is useful to distinguish the input power W_i from the radiated power W_r . We shall write

$$(95) \quad W_r = \eta W_i,$$

where η is a positive number ≤ 1 , which is called the *efficiency* of the antenna.

It is customary to call *gain* the ratio of the maximum intensity radiated by the antenna to the intensity radiated by an isotropic antenna having the same input power and ideal efficiency $\eta=1$. Thus we have for the gain G

$$(96) \quad G = \frac{4\pi U_m}{W_i} = \frac{4\pi\eta U_m}{W_r} = \eta\Delta.$$

Gain is usually expressed in db, by taking 10 times the logarithm to the base 10 of G .

7. - Effective cross-sections.

Let a plane wave impinge on an antenna. If S is the Poynting vector of the wave in watt/m² and W_c is the power collected by the antenna, *i.e.* the power removed from the plane wave, the ratio

$$(97) \quad A_c = \frac{W_c}{S}$$

will be termed the *collecting cross-section* of the antenna.

The collected power W_c can be divided into three portions. A portion W_s will be scattered (re-radiated), a second portion W_d will be dissipated into heat in the antenna, the third portion W_l will be transferred to the load (re-

ceiver) which is connected to the antenna. Correspondingly, we will define a *scattering cross-section*

$$(98) \quad A_s = \frac{W_s}{S},$$

a *dissipation cross-section* (or loss cross-section)

$$(99) \quad A_d = \frac{W_d}{S}$$

and a *receiving cross-section* (sometimes called effective cross-section)

$$(100) \quad A_r = \frac{W_t}{S}.$$

We shall evidently have

$$(101) \quad A_s + A_d + A_r = A_c.$$

Finally we have the *geometrical* or physical cross-section A_g equal to the area of the shadow which the antenna would project according to geometrical optics on a screen perpendicular to the direction of the impinging wave.

Contrary to what might appear, the collecting cross-section of a large lossless antenna does not approach the geometrical cross-section. For instance, in the case of a mirror $A_c \simeq 2A_g$, since $A_s \simeq A_g$ and $A_r \simeq A_g$.

8. - The equivalent circuit.

It is instructive to set up an equivalent circuit (Fig. 24), where the antenna is considered as a generator having an electromotive force V equal to the e.m.f. induced by the impinging wave in the antenna and an internal impedance Z_A , connected to a load Z_L . We shall have

$$(102) \quad Z_A = R_r + R_d + iX_A,$$

where R_r is the radiation resistance, R_d the loss resistance and X_A the reactance of the antenna. Also we shall put

$$(103) \quad Z_L = R_L + iX_L.$$

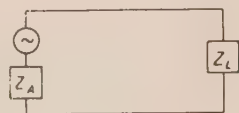


Fig. 24.

Denoting by V_0 and I_0 the effective values of the voltage and current, we find

$$(104) \quad I_0 = \frac{V_0}{\sqrt{(R_r + R_d + R_L)^2 + (X_A + X_L)^2}},$$

the received power will then be

$$(105) \quad W = \frac{V_0^2 R_L}{(R_r + R_d + R_L)^2 + (X_A + X_L)^2}$$

and the receiving cross-section

$$(106) \quad A_L = \frac{V_0^2 R_L / S}{(R_r + R_d + R_L)^2 + (X_A + X_L)^2}.$$

To make A_L a maximum for a given antenna, one has first to orient the antenna so as to have the maximum induced voltage V_{max} , then to choose a load such that $X_L = -X_A$ and $R_L = R_r + R_d$. Thus we obtain the maximum receiving cross-section

$$(107) \quad A_{L \text{ max}} = \frac{V_{\text{max}}^2}{4S(R_r + R_d)}.$$

The scattering cross-section will be given by

$$(108) \quad A_s = \frac{V_0^2 R_r / S}{(R_r + R_d + R_L)^2 + (X_A + X_L)^2}$$

and the dissipation cross-section by

$$(109) \quad A_d = \frac{V_0^2 R_d / S}{(R_r + R_d + R_L)^2 + (X_A + X_L)^2}.$$

In the conditions of maximum reception we will have

$$(110) \quad A_s + A_d = A_{L \text{ max}}.$$

If the antenna is lossless, the *scattering* cross-section is equal to the reception cross-section.

In some cases (parasitic elements) one is interested in having a large scattering cross-section. It is evident from (108) that one should make $X_L = -X_A$ (resonant system) and $R_L = 0$. If the antenna is lossless, we simply find

$$(111) \quad A_{s \text{ max}} = V_{\text{max}}^2 / SR_r.$$

Upon comparison with (107), we see that the maximum scattering cross-section is four times the maximum reception cross-section.

For a short dipole, we have $V_{\max} = El$, where E is the effective value of the electric field and according to (89), $R_r = 80\pi^2 l^2 / \lambda^2$.

Since $S = E^2 / Z_0$, we easily find

$$(112) \quad A_{L \max} = \frac{3}{8\pi} \lambda^2 = 0.12 \lambda^2$$

and four times as much for the maximum scattering cross section.

9. - Half-wavelength antenna.

We have already remarked that for antennae like those shown in Fig. 25-*a*), *b*), *c*), it is a good approximation to assume that the current distribution remains the same as that of the open-circuited two-wire line. Consequently antenna *a*) having a length $l < \lambda/2$ presents the line a capacitive

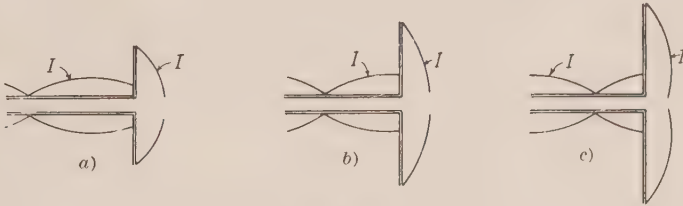


Fig. 25.

impedance, antenna *c*), with $l > \lambda/2$ presents an inductive impedance. Antenna *b*) has $l = \lambda/2$ and is therefore at resonance. It is equivalent to a pure resistance (radiation resistance plus loss resistance). This is the most interesting type of linear antenna.

Taking the linear antenna as z axis and the origin at the center of the antenna, the current distribution will be

$$(113) \quad I = I_0 \sin [\beta(l/2 \mp z)]$$

the upper sign being used for $z > 0$ and the lower sign for $z < 0$. The field radiated from the linear antenna is easily found by integrating, with the proper phase, the contributions of all the linear dipoles into which the current distribution can be decomposed. The result for the far field is

$$(114) \quad E_\theta = 60 i I_0 \frac{\exp[-i\beta r]}{r} \frac{\cos(\beta(l/2) \cos \theta) - \cos(\beta(l/2))}{\sin \theta},$$

$$(115) \quad H_\phi = \frac{i}{2\pi} I_0 \frac{\exp[-i\beta r]}{r} \frac{\cos(\beta(l/2) \cos \theta) - \cos(\beta(l/2))}{\sin \theta}.$$

In the case of the $\lambda/2$ antenna, we have

$$(116) \quad E_{\theta} = 60 i I_0 \frac{\exp[-i\beta r]}{r} \frac{\cos\{(\pi/2) \cos \theta\}}{\sin \theta}.$$

The $\lambda/2$ antenna has a doughnut radiation pattern with half-power beam width $\theta_0 = 78^\circ$. This may be compared with the value $\theta_0 = 90^\circ$ for the short dipole.

The total power radiated by a linear antenna is found by integrating the Poynting vector over a large sphere. As a result one can compute the radiation resistance. For the $\lambda/2$ antenna it is found

$$(117) \quad R_r = 73 \, \Omega.$$

More accurate computations require to take into account the thickness of the antenna. The theory becomes rather complicated. For a cylindrical antenna it leads to an integral equation for the current distribution (Hallén's integral equation), which can be solved by successive approximations. The corrections with respect to the simplified theory presented above are not found to be very important for a thin antenna. It turns out that the $\lambda/2$ antenna has, besides the radiation resistance, some positive input reactance. In order to make it resonant it is therefore necessary to make it a little shorter. It also turns out that the energy stored around the cylinder and consequently the Q of the antenna decrease when the radius of the cylinder increases. Thus a thick antenna can be rather broad band.

10. — Folded dipole.

Consider the antenna of Fig. 26 which is called the folded dipole. If we admit the current to retain its value along the wire as if it were a normal section of the line, we see that at two corresponding points of the folded portion like A , B , it has exactly the same value and direction. Therefore the far field will be twice that radiated by a simple $\lambda/2$ antenna. Consequently the power and the radiation resistance will be four times those of the $\lambda/2$ antenna. The value of the radiation resistance will be slightly less than $300 \, \Omega$, so that

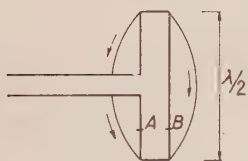


Fig. 26.

the folded dipole can be well matched to a proper two-wire transmission line.

11. - Line arrays.

Fig. 27 represents a *line array* of identical elements, which will be assumed to be equispaced and have identical orientation. Let us take as z -axis the line along which the elements are distributed, and represent each element simply by a point (Fig. 28). Let $I_1, I_2, \dots, I_n$ represent the currents in the first, second, ..., n -th

element respectively. We will assume that the field radiation pattern of a single element is known. For the k -th element it will have the form $I_k f(\vartheta, \varphi)$. It is seen from the figure that the radiation sent by any element in the direction ϑ, φ must travel a path longer by $d \cos \vartheta$ than the radiation from the preceding element. Therefore the resultant field will be

$$\begin{aligned} (118) \quad E &= I_1 f(\vartheta, \varphi) + I_2 f(\vartheta, \varphi) \exp [-i\beta d \cos \vartheta] + \\ &+ I_3 f(\vartheta, \varphi) \exp [-2i\beta d \cos \vartheta] + \dots + I_n f(\vartheta, \varphi) \exp [-(n-1)i\beta d \cos \vartheta] = \\ &= f(\vartheta, \varphi) \sum I_k \exp [-(k-1)i\beta d \cos \vartheta]. \end{aligned}$$

The sum is called the *array pattern*. We thus find the result that the total field pattern is the product of the element pattern $f(\vartheta, \varphi)$ and the array pattern. This is a very useful theorem, which will allow us to investigate array patterns separately. More precisely we will consider all arrays as being constituted of isotropic elements.

It is an easy matter to show that the same theorem holds also for *surface arrays* and for *space arrays*.

12. - End-fire and broad-side arrays.

The current I_k is, in general, a complex number. For convenience, we will stipulate that I_k denotes only the modulus and replace the current I_k in (118) by $I_k \exp [i\varphi_k]$, where φ_k is the phase. In most applications one makes $\varphi_k = -(k-1)\delta$, where δ is the constant phase lag of each element with respect to the preceding one. The array pattern then takes the form

$$(119) \quad A = \sum I_k \exp [-i(k-1)(\beta d \cos \theta + \delta)].$$

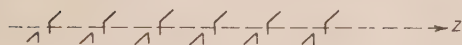


Fig. 27.

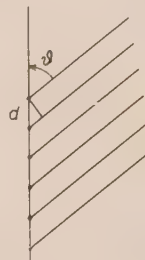


Fig. 28.

The maximum of the array pattern is in the direction in which all terms are in phase. If $\beta d = -\delta$ the maximum occurs for $\theta = 0$ and we obtain an *end-fire array*. If $\delta = 0$, the maximum is for $\theta = \pi/2$ and we have a *broad-side array*.

An important case is when all the I_k 's are equal to I . Then, by putting

$$(120) \quad \psi = \beta d \cos \theta + \delta,$$

we obtain

$$(121) \quad \begin{aligned} A &= I [1 + \exp[-i\psi] + \exp[-i2\psi] + \dots + \exp(-i(n-1)\psi)] = \\ &= I \frac{1 - \exp[-in\psi]}{1 - \exp[-i\psi]} = I \exp\left[-i \frac{n-1}{2} \psi\right] \frac{\exp[i(n/2)\psi] - \exp[-i(n/2)\psi]}{\exp[i(\psi/2)] - \exp[-i(\psi/2)]} = \\ &= I \exp\left(-i \frac{n-1}{2} \psi\right) \frac{\sin(n\psi/2)}{\sin \psi/2}, \end{aligned}$$

hence, apart from a constant, the power pattern of an array of isotropic sources is given by

$$(122) \quad P = \frac{\sin^2 n(\psi/2)}{\sin^2 (\psi/2)}.$$

The pattern is represented in Fig. 29 as a function of ψ for $n = 10$. The pattern has a major maximum every time ψ becomes a multiple of 2π . If we want only the first major maximum ($\psi = 0$) to be present, we must require

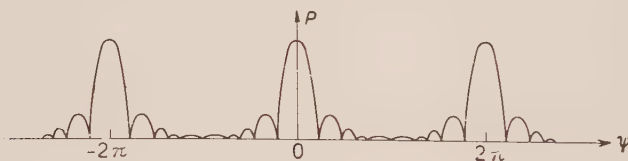


Fig. 29.

$|\psi| < 2\pi$. For a broad-side array this condition is satisfied by any real θ if $d < \lambda$. For an end-fire array we must have $d < \lambda/2$.

Conventionally, we will assume the beam-width θ_0 to be characterized by the angular distance between the first maximum and the first null of the pattern. An easy calculation shows that for a long end-fire array ($nd \gg \lambda$), we have

$$(123) \quad \theta_0 = \sqrt{\frac{2\lambda}{nd}}.$$

Thus, if we call $D = nd$ the length of the array, we obtain

$$(124) \quad \theta_0 = \sqrt{\frac{2\lambda}{D}},$$

in the case of a long broad-side array the result would be instead

$$(125) \quad \theta_0 = \frac{\lambda}{D}.$$

Of course, one should remember that, for isotropic sources, the main lobe of the broad-side array has the width θ_0 in both directions, while the main lobe of the broad-side array is thin in the meridional plane only, and is isotropic around the axis.

13. - Parasitic elements.

Sometimes the elements of an array are not all directly energized. Some of the elements simply re-radiate the energy which they receive from the others and are called parasitic.

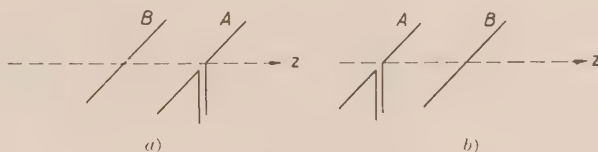


Fig. 30.

Consider, for instance, the two-element array of Fig. 30. The parasitic element B is excited by the field created by the driven element A . The prediction of the voltage induced in B by a given current in A requires the solution of a difficult problem (computation of the *mutual impedance*), which can be solved either mathematically

or experimentally. In this way one can adjust the system for the end-fire condition ($\beta d = -\delta$). It is found that for a spacing ($d < \lambda/4$), which is customary, one should make B inductive, *i.e.* longer than $\lambda/2$, in order to have end-fire radiation in the direction

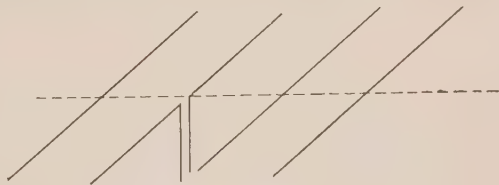


Fig. 31.

of the positive z -axis (B to A). In this case B acts as a *reflector*. On the contrary, if B is made capacitive, *i.e.* shorter than $\lambda/2$ (Fig. 30 *b*)), end-fire radiation will occur in the direction A to B . In this case B is called a *director*. An array can have one or more reflectors and one or more directors at the same time (yagi arrays). A typical example is given in Fig. 31.

14. - Helical antenna.

An end-fire array of considerable interest is the *helical antenna* (Fig. 32). Several different modes can be entertained by a helical conductor. However, the one that prevails when the length L of one turn is of the order of one



Fig. 32.

wavelength is with great approximation represented by a simple wave traveling along the conductor with a phase velocity v slightly smaller than c . It is then possible to obtain the condition that two corresponding points like A and B

should send in-phase radiation in the direction of the axis z . Indeed, if we put $p = v/c$ the wavelength along the conductor will be $p\lambda_0$ and the condition for end-fire radiation is readily found to be

$$(126) \quad \frac{L}{\lambda_0 p} = \frac{d}{\lambda_0} + 1,$$

where d represents the spacing between A and B . This can also be written

$$(127) \quad L = p(d + \lambda_0).$$

Surprisingly enough, a rigorous argument as well as experiment, show that this condition is satisfied with good approximation for an entire band of wavelengths in the vicinity of $\lambda_0 \simeq L$. Thus the helical antenna has a good end-fire pattern for a relatively broad band. Its radiation resistance is in the range of $(100 \div 200) \Omega$. It is evident from symmetry considerations that the radiation will be circularly polarized.

15. - Reflectors.

Reflectors and other optical devices are used when the passage between the transmission line and free space takes place in two stages. First, energy from the transmission line is converted into a spherical wave, then the spherical wave is converted into a plane wave.

For instance, in the case of the paraboloid represented in Fig. 33, the horn matches the impedance of the waveguide mode to that of a spherical

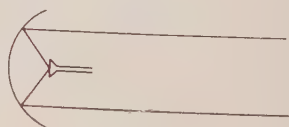


Fig. 33.

wave, while the paraboloid matches the impedance of the spherical wave to that of the plane wave.

16. – Radiation from a plane aperture.

The paraboloid reflector, the lens, the horn can be considered as particular cases of radiation from a plane surface of limited extent (*aperture*). The radiation pattern can be evaluated as follows.

Suppose the field distribution $f(x, y)$ over the aperture is known. If we can find a set of plane waves traveling from half-space $z < 0$ into space $z > 0$, which when superimposed on the plane $z = 0$, give rise to the field $f(x, y)$, these waves will represent the radiation produced by the aperture (principle of *inverse interference*). A single plane wave is represented by

$$F \exp [-ik(\alpha x + \beta y + \gamma z)],$$

where $k = 2\pi/\lambda$ and α, β, γ , are the direction cosines of the normal. If we assume the amplitude F to be a function of the direction and superimpose an infinite set of such waves, we shall obtain at $z = 0$

$$(128) \quad f(x, y) = \iint F(\alpha, \beta) \exp [-ik(\alpha x + \beta y)] d\alpha d\beta.$$

If we make the limits of integration $-\infty, +\infty$ for both α and β , (128) is a Fourier integral, and we obtain

$$(129) \quad F(\alpha, \beta) = \frac{1}{\lambda^2} \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} f(x, y) \exp [ik(\alpha x + \beta y)] dx dy.$$

Hence we derive the conclusion that the field radiation pattern $F(\alpha, \beta)$ represents the Fourier spectrum of the aperture distribution. Conversely, the aperture distribution represents the frequency spectrum of the field radiation pattern. Therefore the spectrum of the field radiation pattern is limited.

The power radiation pattern $|F(\alpha, \beta)|^2$, by the reciprocity theorem, will represent the response to radiation coming from the direction α, β . If we interpret α, β as *angular frequencies* in space or *spacial frequencies*, we may say that each spacial frequency is filtered by the antenna through a filter $|F(\alpha, \beta)|^2$.

If the antenna is turning or scanning the sky and at a certain time is

pointed towards α_0, β_0 , the total response $R(\alpha_0, \beta_0)$, will be apart from a constant factor (*)

$$(130) \quad R(\alpha_0, \beta_0) = \iint I(\alpha, \beta) |F(\alpha - \alpha_0, \beta - \beta_0)|^2 d\alpha d\beta,$$

where $I(\alpha, \beta)$ is the intensity distribution of the source. This is a *convolution* integral. As is well known, the spectrum r of R is the product of the spectrum γ of I and the spectrum $\bar{f}$ of $|F|^2$

$$(131) \quad r = \gamma \bar{f}.$$

Now if the spectrum of F is frequency limited, also the spectrum of $|F|^2$ is frequency limited. Hence $\bar{f}$ will be zero for frequencies exceeding a given limit. The same will be true for r . This means that although the source distribution I is an arbitrary function, the response function R or *image* of the source is not arbitrary.

Alternatively we may say that many different source distributions may have one and the same image.

In order to make a decision and to select the right distribution, one must have some information *a priori* about the source. This is of particular importance in radio astronomy, where the possible shapes of the sources are less known than in optical astronomy.

(*) Relation (130) is true only for small α, β , since α and β are not angles, but sines of angles. For an exact argument, see G. TORALDO DI FRANCA, *I.R.E. Trans.* Vol. A. P. 4, 473 (1956).

Radioémission d'origine solaire.

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Introduction.

Prévue en 1894 par Sir OLIVER LODGE, recherchée vainement à la fin du siècle dernier et au début de ce siècle par SCHEINER et WILSING et par NORDMANN, soupçonnée en 1938 par ARAKAWA, la radiation hertzienne d'origine solaire ne fut vraiment mise en évidence qu'en 1942 par J. S. HEY et F. J. M. STRATTON pour les émissions de haute intensité liées aux phénomènes d'activité solaire, et en 1945 par G. C. SOUTHWORTH pour les émissions du Soleil calme. Cette mise en évidence suivait donc d'assez loin la découverte de la radiation hertzienne d'origine galactique par K. G. JANSKY (1932-1935) et les premières mesures de G. REBER. Un tel fait traduit bien la faiblesse en tant qu'émetteur radioélectrique du Soleil, étoile normale de la séquence principale, par rapport aux autres sources cosmiques. Cependant, cette découverte permit à la physique solaire de bénéficier d'un nouveau domaine spectral, ce qui lui fit faire des progrès importants. A ce sujet, une comparaison des domaines optiques et radioélectriques s'impose.

1) L'étude du spectre optique a fourni la plupart des résultats obtenus en physique solaire jusqu'en 1945 environ. Ce spectre consiste en un fond continu entrecoupé de nombreuses raies d'absorption (raies de Fraunhofer). Sur le fond continu, le Soleil apparaît plus brillant au centre qu'au limbe et cette propriété résulte évidemment de ce que la radiation s'échappant sous un certain angle avec la normale doit traverser plus de gaz froids que la radiation s'échappant normalement. De la courbe d'obscurcissement centre-limbe et de la courbe énergie-longueur d'onde, on peut déduire moyennant l'équation de transfert radiatif des informations précieuses sur la photosphère. Ces informations sont à la base de notre étude de l'intérieur de l'étoile en fournissant les conditions aux limites des équations d'équilibre. Les raies

spectrales, elles, dépendent de plus de paramètres que le fond continu et nous fournissent des informations souvent meilleures. Elles nous permettent d'aborder également des milieux plus extérieurs. C'est ainsi que la chromosphère, complètement transparente sur le fond continu, présente une épaisseur optique non négligeable sur la raie H_α de l'hydrogène, et devient observable directement sur les spectrohéliogrammes et les filtrogrammes. La couronne solaire est également transparente sur le fond continu et n'est observable que pendant les éclipses totales ou au moyen de coronographes. Cependant, sur certaines raies, la couronne devient optiquement épaisse. Malheureusement, les couches coronales atteintes par ces procédés sont toujours des couches très basses; si l'on excepte les observations de la lumière zodiacale, la haute couronne est inaccessible aux observations optiques.

Les clichés obtenus dans le domaine optique présentent une grande finesse et révèlent de nombreux détails. Mais l'étendue du domaine spectral ainsi étudié est très faible (trois octaves à peine en longueur d'onde). Les mesures actuelles au moyen d'engins spatiaux (fusées et satellites) permettent de l'étendre du côté de l'ultraviolet et de la radiation X. L'extension du côté de l'infrarouge demandera vraisemblablement la mise au point de techniques particulières.

Si l'on excepte certaines variations très faibles et limitées à des régions spectrales particulières du domaine optique (raies, continuum X), le Soleil se présente dans ce domaine comme une étoile extrêmement *stable*. Sur le fond continu du spectre, l'éclat du Soleil est rigoureusement constant.

2) Le spectre radioélectrique solaire ne présente pas la richesse d'informations du spectre optique car il est essentiellement dépourvu de raies. Cependant, la nature des processus mis en jeu lors des émissions radioélectriques permanentes des couches extérieures (transitions free-free dans un milieu ionisé à haute température) est telle que ces couches sont optiquement épaisses même à des distances considérables du limbe. De plus, ces couches présentent un indice de réfraction non négligeable aux fréquences radioélectriques. Enfin, elles agissent comme un élément diffusant. Aux diverses fréquences, la distribution de brillance du Soleil calme est différente. Comme la température coronale ne diminue pas vers l'extérieur de la même manière, ni d'une façon aussi rapide que la température dans l'épaisseur de la photosphère, on n'observe pas toujours un obscurcissement centre-limbe et, aux fréquences élevées, il y a au contraire éclaircissement. De plus, la distribution de brillance ne possède pas toujours la symétrie sphérique. Moyennant l'équation de transfert radiatif, et en se basant sur la distribution de brillance observée, on pourra tirer des observations radioélectriques des informations sur les couches les plus extérieures. Ainsi, la presque totalité de la radiation solaire sur ondes métriques est d'origine *coronale*, et de fait, seules les observations radioélectriques peuvent nous informer sur les conditions physiques de la haute couronne. Quant à la chromosphère, celle-ci pose encore des problèmes difficiles surtout

dans la région de transition avec la couronne où l'élévation rapide de la température et de l'ionisation a lieu dans une zone étroite non toujours accessible au pouvoir résolvant des instruments radioastronomiques.

La création d'images radioélectriques solaires est une question liée au pouvoir résolvant des instruments actuels. Aux grandes longueurs d'onde, le pouvoir résolvant reste faible. Les distributions de brillance obtenues jusqu'à présent dans le domaine hertzien résultent soit d'un calcul, soit de techniques encore peu évoluées. Elles ne présentent aucunement la finesse des images optiques. L'étendue du domaine spectral radioélectrique est très grande (quelque 15 octaves) mais le complément d'informations que ce domaine fournit par rapport au domaine optique n'est nullement proportionnel à l'étendue spectrale. Il est également fort possible que, dans un proche avenir, des observations radioélectriques soient effectuées à bord d'engins spatiaux, nous dégageant ainsi des absorptions par l'atmosphère terrestre (absorption ionosphérique aux ondes longues, absorption moléculaire aux ondes courtes).

Par contre, le domaine radioélectrique se différencie du domaine optique par une propriété fondamentalement intéressante: nous savons que sur le fond continu optique l'éclat du Soleil est constant, au contraire, sur le fond continu radioélectrique le Soleil se présente comme une étoile essentiellement variable. Il n'est pas rare d'observer, sur ondes métriques, des sursauts de radiation d'une intensité mille fois plus forte que la radiation permanente. Ces variations sont toujours temporaires. Elles sont liées à des phénomènes d'activité mais ceux-ci n'ont pas toujours un correspondant optique. Les fortes intensités observées au cours de sursauts excluent l'hypothèse d'une radiation thermique car les températures mises en jeu s'élèveraient parfois à 10^{13} °K. Ainsi, les processus d'émission radioélectrique peuvent être très différents des processus d'émission optique. Il est donc nécessaire de distinguer ici:

- a) la radiation du Soleil calme (origine thermique);
- b) la radiation du Soleil actif (origine généralement non thermique).

Les émissions thermiques sont dues à des mouvements *désordonnés* d'électrons en présence d'ions (accélérations lorentziennes ou transitions free-free); les émissions non thermiques sont, la plupart du temps, dues à des mouvements *coordonnés* d'électrons (ondes de plasma, radiation de synchrotron); elles mettent clairement en évidence le rôle des champs magnétiques.

Ainsi, la considération de nouveaux processus d'émission devient nécessaire. En retour, ces processus nous aident à comprendre la nature des phénomènes optiques. Pour la physique solaire, un nouvel horizon s'est ainsi déployé.

3) Rappelons la relation bien connue

$$\lambda\nu = c,$$

(λ = longueur d'onde, ν = fréquence). Dans le système MKS, $c = 3 \cdot 10^8$ m·s⁻¹.

Ordinairement la fréquence s'exprime en cycles par seconde (c/s) ou en hertz ($1 \text{ Hz} = 1 \text{ c/s} = 1 \text{ s}^{-1}$). Les multiples suivants sont fréquemment utilisés: $1 \text{ kc/s} = 10^3 \text{ c/s}$; $1 \text{ Mc/s} = 10^6 \text{ c/s}$; $1 \text{ Gc/s} = 10^9 \text{ c/s}$; etc. (kilocycle, mégacycle, gigacycle, etc., par seconde). L'unité Hz figure dans certaines normes nationales en Europe et vient d'être adoptée par l'U.I.T. (1959).

Quand on exprime ν en MHz et λ en mètres:

$$\lambda_m = \frac{300}{\nu_{\text{MHz}}}$$

Conformément à un avis du CCIR, le domaine radioélectrique se divise comme suit dans la région intéressante pour la Radioastronomie:

TABLEAU I.

Ondes décamétriques (Dm)	(100 $\div$ 10) m	(3 $\div$ 30) MHz	HF bande 7 (CCIR)
métriques (m)	(10 $\div$ 1) m	(30 $\div$ 300) MHz	VHF bande 8
décimétriques (dm)	1 m $\div$ 10 cm	(300 $\div$ 3 000) MHz	UHF bande 9
centimétriques (cm)	(10 $\div$ 1) cm	(3 $\div$ 30) GHz	SHF bande 10
millimétriques (mm)	1 cm $\div$ 1 mm	(30 $\div$ 300) GHz	EHF bande 11

Les adjectifs HF, VHF, etc., sont mentionnés à titre indicatif, mais ne sont pas repris par le CCIR [1].

Le domaine d'intérêt pour la Radioastronomie est limité vers les courtes longueurs d'onde par l'absorption moléculaire (bandes de rotation-vibration ou de rotation pure des molécules asymétriques, en particulier la vapeur d'eau). Cette absorption est particulièrement intense dans la troposphère. L'absorption par la vapeur d'eau est encore importante à $\lambda = 1.5 \text{ cm}$; elle disparaît aux ondes décimétriques.

Aux grandes longueurs d'onde (décamétriques) l'absorption a lieu dans

l'ionosphère. Les ondes les plus longues sont absorbées aux niveaux les plus élevés des

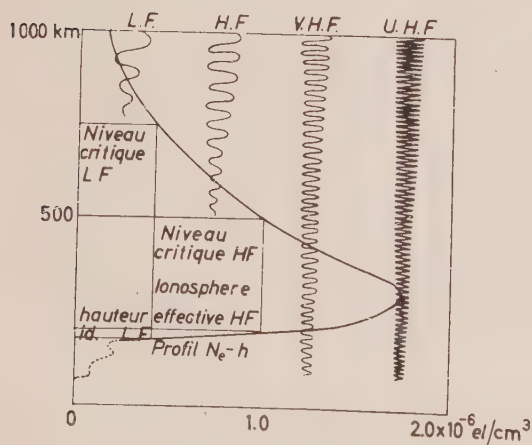


Fig. 1. - Pénétration des ondes radioélectriques d'origine extérieure dans l'ionosphère. Aux basses fréquences (LF, HF, décamétriques), il existe un niveau critique au-dessous duquel les ondes ne peuvent se propager. Aux hautes fréquences (VHF, UHF; m, dm, cm, etc.) les ondes pénètrent en s'amortissant. Cet amortissement est très faible aux ondes très courtes.

couches ionosphériques comme l'indique la Fig. 1 (schématique), du fait que le coefficient d'absorption d'un milieu ionisé varie comme N_e^2/ν^2 (N_e — nombre d'électrons libres par unité de volume).

La Fig. 2 donne une représentation schématique des divers facteurs d'absorption atmosphérique sur l'ensemble du spectre électromagnétique. On y observe, en particulier, l'étroitesse de la fenêtre optique par rapport à la fenêtre radioélectrique.

Dans la couronne solaire, le phénomène inverse a lieu. Comme l'émissivité d'une couche à l'équilibre thermodynamique local est proportionnelle à son pouvoir absorbant, et comme la densité électronique coronale diminue avec l'altitude croissante, les ondes longues et les ondes courtes sont émises aux hauts niveaux dans la couronne, tandis que les bas niveaux ne fournissent plus que des ondes courtes. Nous précisons ultérieurement ce point. Dès à présent néanmoins, nous pouvons constater que les observations radioélectriques aux diverses longueurs d'onde permettent de réaliser en quelque sorte des coupes optiques dans l'atmosphère solaire.

Dans ces conférences, on s'est proposé de décrire d'une manière assez générale deux aspects de la radioastronomie solaire. Nous traiterons d'abord des *techniques instrumentales* (antennes, radiomètres); nous examinerons ensuite les principaux caractères de la *radiation hertzienne solaire* (le Soleil calme, le Soleil actif).

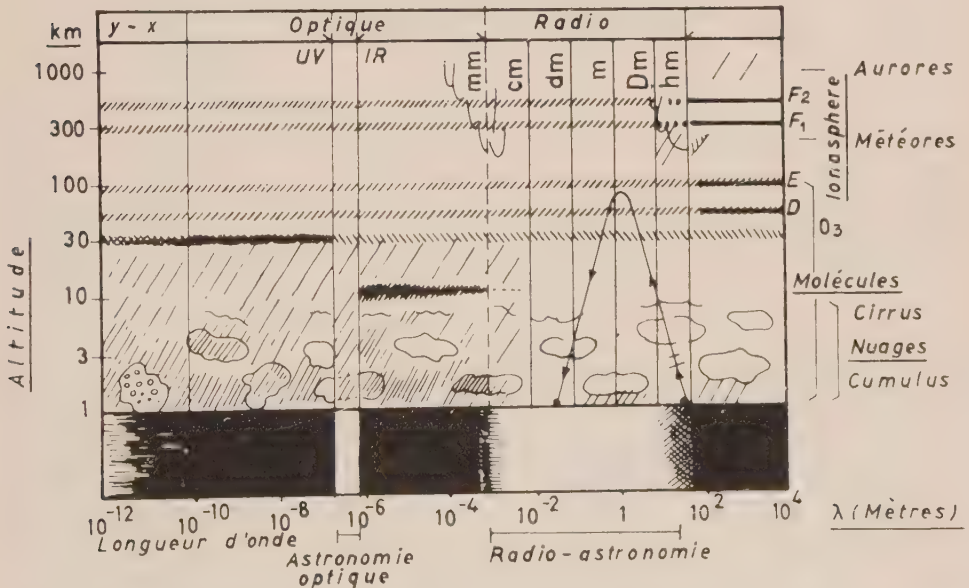


Fig. 2. — Facteurs d'absorption atmosphérique. En ordonnées, altitude en km. En abscisses, longueur d'onde en m. Dans le bas, les fenêtres d'observation.

PREMIÈRE PARTIE

TECHNIQUES INSTRUMENTALES EN RADIOASTRONOMIE SOLAIRE

I. — L'aérien.

1. — Description schématique du radiotélescope.

L'instrument typique utilisé en radioastronomie solaire est représenté Fig. 3. Un radiotélescope simple se compose principalement d'une *antenne directive* connectée par une ligne de transmission à un *radiorécepteur* sensible. L'antenne

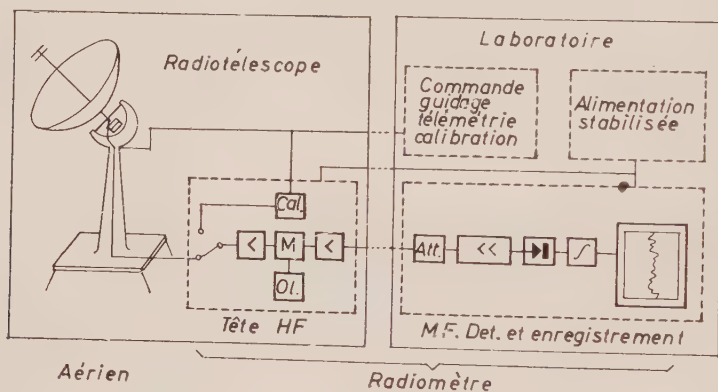


Fig. 3. — Schéma d'un radiotélescope simple. Aérien parabolique avec un dipôle au foyer. Première partie du récepteur localisée à proximité de l'antenne. Au laboratoire, seconde partie du récepteur et dispositifs d'alimentation, de commande et d'enregistrement.

exposée à la radiation, qui induit sur elle des courants variables, se comporte comme un générateur de force électromotrice de sorte qu'à l'extrémité opposée de la ligne, sur l'impédance d'entrée du récepteur, apparaît une tension variable. Comme la radiation est d'origine naturelle et comme elle est due à un grand nombre de processus se produisant au hasard, il ne s'agit pas d'une tension purement alternative. Au contraire, la tension apparaissant aux bornes d'entrée du récepteur doit être considérée plutôt comme un « bruit » électrique, fonction aléatoire du temps qui comprend une infinité de composantes de fréquence distribuées sur un spectre continu. Les propriétés sélectives de l'antenne, et

principalement celles du récepteur, isolent sur ce spectre un intervalle plus ou moins étroit de sorte que la mesure prend un caractère quasi-monochromatique.

Le type d'antenne diffère suivant la fréquence centrale et la bande de fréquence à analyser. Il existe des antennes pour ondes métriques, des antennes pour microondes, des antennes à bande étroite ou à large bande, etc. Il est important de mentionner ici que l'antenne est toujours un élément polarisé, sélectionnant une seule composante de polarisation dans l'onde incidente (*). De plus l'antenne est caractérisée à chaque fréquence et pour chaque polarisation par son diagramme de directivité, ou indicatrice de réception (Fig. 4). On obtient expérimentalement cette indicatrice en laissant passer une source

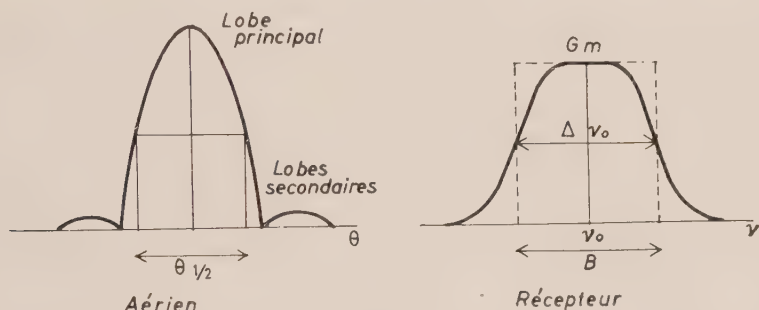


Fig. 4. — Diagramme d'antenne (lobe principal et lobes secondaires): sélection des fréquences spatiales. Bande passante du récepteur (fréquence centrale et largeur de bande): sélection des fréquences temporelles.

fine (par exemple une radiosource galactique) dans le champ de l'antenne sous diverses inclinaison et en observant la réponse du récepteur; une telle indicatrice dépend de la géométrie de l'antenne; elle est caractérisée le plus souvent par la présence de lobes dont l'un (lobe principal) est plus important que les autres (lobes secondaires); dans ce cas, l'angle d'ouverture à mi-intensité $\theta_{1/2}$ du lobe principal peut servir à qualifier le pouvoir résolvant du radiotélescope. Comme $\theta_{1/2}$ est toujours de l'ordre de λ/D , où D qualifie l'étendue géométrique de l'antenne, ce pouvoir résolvant n'est jamais élevé. Par exemple un miroir parabolique avec un dipôle au foyer, et d'un diamètre de 120 m, a un pouvoir résolvant de $30'$ à $\lambda = 1$ m. Comme le problème du pouvoir résolvant est fondamental en radioastronomie, on est conduit à utiliser divers artifices dont les principaux consistent en l'utilisation d'antennes interférométriques. Un interféromètre est constitué par deux antennes placées aux extrémités d'une

(*) Ainsi, une antenne dipôle d'axe XY n'est excitée que par la composante XY du vecteur électrique de l'onde incidente.

base, ou par un arrangement d'antennes collinéaires connectées simultanément au récepteur; l'indicatrice d'un tel dispositif est constituée de toute une série de lobes étroits, disposés comme les feuillets d'un livre. Au prix d'un certain risque de confusion, un interféromètre fournit un pouvoir résolvant qu'il serait impossible d'obtenir dans l'état actuel de la technique par la construction de grand paraboloïdes; ces instruments sont d'ailleurs beaucoup moins onéreux (*) mais à cause du risque de confusion, ils ne se substituent pas aux paraboloïdes.

Le récepteur radioélectrique utilisé en radioastronomie est généralement du type superhétérodyne. Il est composé essentiellement d'un *amplificateur* haute fréquence, d'un *mélangeur* où les signaux amplifiés sont combinés à ceux d'un oscillateur local à une fréquence légèrement différente en présence d'un élément non linéaire ce qui a pour effet de produire des battements à la différence des fréquences, d'un *amplificateur sélectif* à cette nouvelle fréquence, (fréquence intermédiaire) d'un *détecteur* ou redresseur (élément non linéaire) ayant pour objet de mettre en évidence l'enveloppe de la tension alternative amplifiée, d'un *circuit intégrateur* où les variations de cette enveloppe sont adoucies et ses fluctuations diminuées, enfin d'un dispositif de *présentation* (enregistreur, écran cathodique, etc.) où les résultats de la mesure peuvent être lus. La présence d'amplificateurs est justifiée seulement par la faible intensité du signal d'antenne; le rôle du détecteur est fondamental car c'est dans cet élément que la puissance à mesurer est dissipée (**). On distingue donc dans le radiorécepteur une section *haute fréquence* (amplificateur, mélangeur, oscillateur local), une partie *moyenne fréquence* (amplificateur, détecteur), une partie *basse fréquence* (intégrateur, éventuellement amplificateur continu, dispositif de présentation). L'amplificateur haute fréquence peut faire défaut; dans ce cas, le signal d'antenne est directement mélangé à celui de l'oscillateur local mais ceci présente certains inconvénients (élévation du bruit de fond). Enfin, il est évident que la structure du récepteur dépend essentiellement de la fréquence et du rôle qu'il est appelé à jouer. Il existe des récepteurs pour ondes métriques, des récepteurs pour microondes, des récepteurs directs, à permutation, à détection synchrone, à corrélation, des récepteurs spectrographiques, panoramiques, etc.

La sélection principale des fréquences est effectuée à l'intérieur du récepteur grâce à ses circuits accordés. Le récepteur est à ce sujet caractérisé par la fréquence centrale ν_0 , et par la forme de la bande d'acceptance ou bande passante (Fig. 4). Cette courbe s'obtient en connectant à l'entrée du récepteur

(*) Le prix de revient d'un grand miroir parabolique varie à peu près comme le cube de ses dimensions linéaires, celui d'un interféromètre à peu près comme la longueur de la base.

(**) Si les signaux d'antenne étaient suffisants, un radiotélescope pourrait consister seulement en une antenne, un circuit sélectif, un détecteur et un appareil de mesure du courant détecté.

un générateur sinusoïdal étalonné et en faisant varier la fréquence du signal injecté sans modifier son amplitude. Ordinairement, le rapport des *puissances* injectées à l'entrée et obtenues à la sortie est porté en ordonnées dans le graphique (bande passante en puissance). La largeur de bande à mi-puissance (à 3 décibels) $\Delta\nu_0$ est la largeur soustendue par la courbe à mi-hauteur; la largeur de bande effective (noise bandwidth) B est celle du rectangle de même aire construit sur la hauteur à la fréquence centrale. Il y a intérêt à ce que la bande passante soit la plus rectangulaire possible, et surtout pour des raisons de stabilité à ce qu'elle présente un sommet plat étendu. Il est important de se souvenir ici que le signal à mesurer se présente toujours sous la forme d'un *bruit* électrique, et que tout récepteur radioélectrique a un bruit de fond interne. Ainsi, toute mesure consiste à détecter les variations du bruit de fond constaté à la sortie du récepteur. Etant donné la faible intensité de la radiation incidente, de telles variations sont souvent minimes, et bien inférieures au niveau de bruit de l'appareil. Aussi faut-il prendre certaines précautions, lors de la construction d'un récepteur radioastronomique, pour réduire le bruit de fond interne au minimum et surtout, pour maintenir son niveau le plus constant possible. Des précautions spéciales doivent aussi être prises pour stabiliser au maximum le coefficient d'amplification du récepteur. La plupart des progrès enregistrés ces dernières années en radioastronomie ont été dus en effet, indépendamment de la construction de grandes antennes, à une lutte constante contre le bruit de fond interne et en vue d'améliorer la stabilité de l'amplification. Les tensions d'alimentation des tubes électroniques doivent également être stabilisées (p. ex. hautes tensions: 250 V à 1/40 000 près; tensions de chauffage: 6,3 V à 1/3 000 près). Nous reviendrons sur le sujet dans les pages qui suivent.

2. — Le pouvoir résolvant.

Nous avons indiqué précédemment que pour une antenne directive simple (à un seul lobe principal), le pouvoir résolvant du radiotélescope est conditionné par l'angle d'ouverture à mi-sensibilité du lobe principal. Si l'angle d'ouverture est supérieur à la distance angulaire de deux sources à séparer, l'opération de séparation devient impossible. Par exemple, si l'angle d'ouverture est supérieur au diamètre du Soleil, il sera impossible d'y localiser les sources d'émission. Le radiotélescope ne pourra servir qu'à mesurer le flux total de puissance émis par la source sur la bande d'acceptance définie par le récepteur et il se comportera en fait, dans cette éventualité, comme un actinomètre. C'est le cas pour presque tous les instruments de surveillance de la radiation solaire.

Donnons rapidement quelques indications sur des instruments à pouvoir résolvant meilleur.

a) *Grands paraboloïdes.* Pour un paraboloïde convenablement « illuminé » par un dipôle au foyer, l'angle d'ouverture à mi-puissance du lobe principal est donné approximativement par la formule

$$\theta_{\frac{1}{2}} = 57 \lambda/D \text{ degrés,}$$

D étant le diamètre de l'ouverture. Il est inutile d'espérer obtenir de très hauts pouvoirs résolvants sur ondes relativement longues à l'aide d'un tel dispositif. A $\lambda = 50$ cm, un paraboloïde de 50 m de diamètre donnerait un faisceau d'ouverture 0.57° , tout à fait insuffisant pour localiser des sources sur le disque solaire.

b) *Interféromètre à deux antennes.* En disposant deux antennes aux extrémités d'une base (Fig. 5) et en les connectant en phase au même récepteur, on obtient une série de franges du type indiqué. Une onde plane incidente $\exp[ikr]$ arrivant sous un angle θ avec la normale induit en effet sur les antennes des tensions ou « phaseurs » $\exp[-ik(D/2)\sin\theta]$ et $\exp[+ik(D/2)\sin\theta]$ dont la somme est détectée quadratiquement, de sorte que l'indicatrice a la forme $\cos^2(k(D/2)\sin\theta)$, avec $k = 2\pi/\lambda$. Pour θ voisin de zéro, les zéros du diagramme sont distants de λ/D . Pour $\lambda = 1$ m et $D = 1$ km, le pouvoir ré-

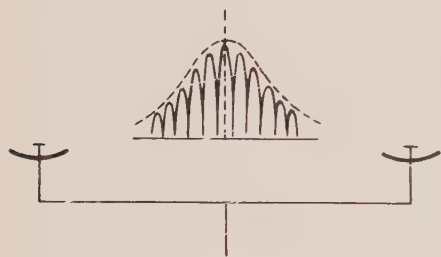


Fig. 5. — Interféromètre à deux antennes. Type de connexion et diagramme (section).

solvant est de l'ordre de 10^{-3} radians ou $3'$ environ. Les franges sont fines, serrées, allongées perpendiculairement à la base. La solution est simple, mais il y a grand risque de confusion. Notons que les franges n'ont d'amplitude sensible qu'à l'intérieur du diagramme de chacune des antennes, ou diagramme primaire.

c) *Interféromètres multiantennes, à suppression de lobes.* En disposant $N = 2^n$ antennes collinéairement à des distances égales d (Fig. 6) on réalise une base de longueur $D = (N-1)d$. Un procédé analogue fournit, pour des antennes en phase, une indicatrice de forme $(\sin Nu/\sin u)^2$, avec $u = \pi d \sin \theta/\lambda$. Cette forme est indiquée sur la figure. On constate de grandes franges très fines, distantes de λ/d (pour θ voisin de zéro), accompagnées de petites franges secondaires. Dans chaque groupe, la finesse des franges est de l'ordre de λ/Nd . Pour $\lambda = 75$ cm, $N = 32$, $d = 20$ m, la finesse est de l'ordre de $3'$ et la

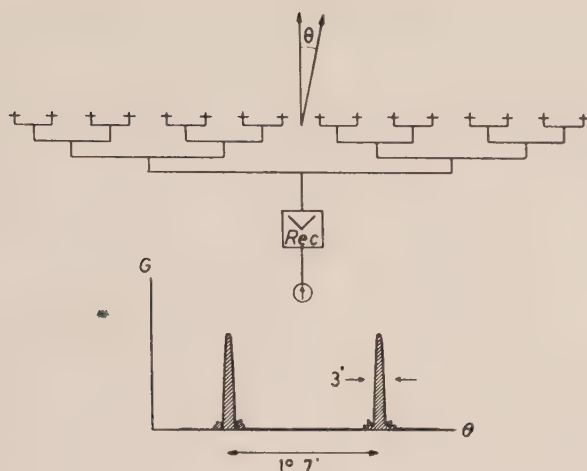


Fig. 6. - Interféromètre multiantenne. Schéma de connexion en phase; type de diagramme (section).

distance interfrange de l'ordre de 2° . Le pouvoir résolvant est élevé; le risque de confusion est très réduit.

d) *Réseaux d'antennes.* $M = 2^m$ réseaux collinéaires de $N = 2^n$ antennes placés parallèlement l'un à l'autre constituent un réseau superficiel fournissant des franges en quadrillage (Fig. 7). La sensibilité est localisée exclusivement aux points d'intersection du quadrillage (gerbe de faisceau étroits). Malheureusement le nombre MN d'antennes individuelles est excessif (pour $M = N = 32$,

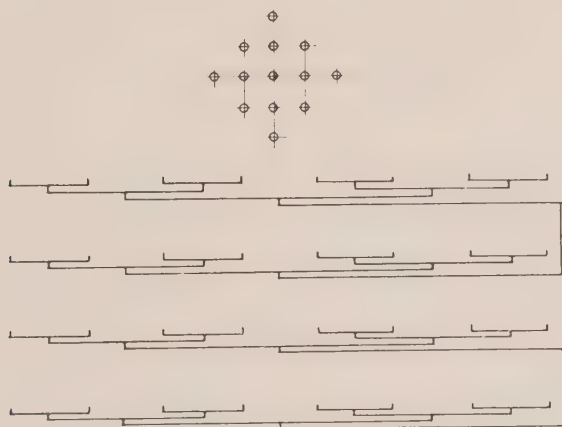


Fig. 7. - Réseau d'antennes. Type de connexions en phase. Le diagramme est constitué d'une série de lobes étroits à l'intersection de deux systèmes de franges orthogonales. Les lobes peuvent être déplacés par déphasage.

MN 1024), ce qui enlève tout intérêt au dispositif. Le système suivant est bien préférable.

c) *Réseaux synthétiques.* Plaçons deux réseaux collinéaires perpendiculairement l'un à l'autre (Fig. 8) mais au lieu d'additionner les phaseurs individuels, multiplions les phaseurs à la sortie de chacun des réseaux l'un par l'autre. Dé-

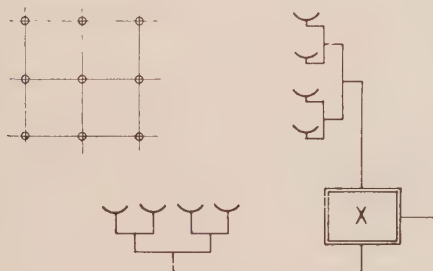


Fig. 8. — Réseau synthétique par multiplication. Diagramme constitué d'une série de lobes étroits. Disposition seulement schématique (ordinairement les deux réseaux forment une croix et non un L; dans certains cas, la disposition est asymétrique).

tectons ensuite quadratiquement (après amplification et même changement de fréquence à condition de conserver les phases). Nous obtenons encore un quadrillage avec une sensibilité maximum aux points d'intersection. Si les phaseurs individuels sont pris à des fréquences voisines et si la différence de ces fréquences est négligeable vis-à-vis de leur valeur moyenne, une nouvelle détection quadratique fournit une indicatrice de la forme

$$\left(\frac{\sin Nu}{\sin u} \right)^2 \cdot \left(\frac{\sin Mv}{\sin v} \right)^2,$$

u et v se rapportant aux angles θ , ψ que fait la direction de propagation de l'onde avec les normales aux deux alignements et ayant la signification donnée à la Section 2, c). Nous avons constitué ainsi un réseau synthétique ne contenant que $M + N$ antennes et ayant les mêmes propriétés directives qu'un réseau superficiel de MN antennes. Nous n'envisageons pas ici la question de redondance d'information. L'analyse de Fourier de chaque alignement montre qu'on peut supprimer certaines antennes sans altérer le pouvoir résolvant. De tels calculs ont été effectués (ARSAC [2]). Cependant la mise en phase de réseaux incomplets ou asymétriques est difficile.

La multiplication des deux phaseurs peut être *immédiate*, ou peut être *différée*. Pour le principe de la multiplication différée, nous renvoyons à l'ar-

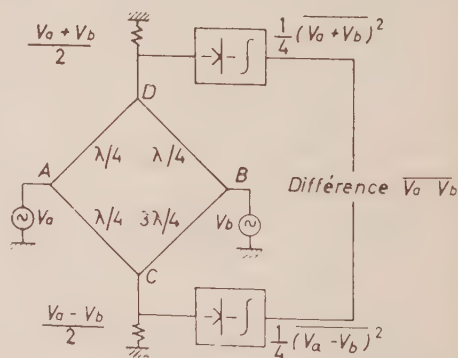


Fig. 9. — Disposition schématique d'un multiplicateur « immédiat ». L'instrument comprend un « anneau hybride » ou anneau magique au moyen duquel deux tensions alternatives sont additionnées et soustraites. Formation du produit moyen par détection quadratique et différence.

ticle de J. P. WILD [3]. Décrivons brièvement ici le principe d'une multiplication immédiate; un dispositif typique est représenté Fig. 9. Aux extrémités A et B de l'anneau hybride $ACBD$ ($AC = AD = DB = \lambda/4$, $CB = 3\lambda/4$) appliquons les tensions V_a et V_b provenant de chaque alignement. Le résultat en C et D peut être obtenu en appliquant la théorie des lignes de transmission, mais intuitivement on voit que, du fait de la longueur des côtés de l'anneau, les tensions apparaissant en C et D sont proportionnelles respectivement à $V_a - V_b$ et $V_a + V_b$ (V_a arrivant en phase en C , D tandis que V_b y arrive en opposition de phase). Détectons ensuite quadratiquement ce qui a pour effet de fournir les carrés moyens $(V_a - V_b)^2$ et $(V_a + V_b)^2$. La différence des carrés moyens est égale à $4V_a V_b$. Le produit moyen est ainsi effectué d'une manière continue et immédiatement. Pour réduire le risque de confusion il suffit de s'arranger, en physique solaire, pour que la distance angulaire des faisceaux déliés successifs soit supérieure au diamètre de la couronne solaire à la fréquence considérée.

f) *Diagrammes mobiles*. Considérons un alignement comme celui de la Section 2, c). Au lieu de laisser les antennes en phase, introduisons un déphaseur à chaque antenne de manière à réaliser une différence *progressive* de phase (on voit immédiatement qu'il suffit de placer $N - 1$ déphaseurs). Une rotation de phase de 2π à la première antenne déphasée (c.à.d. $(N - 1)2\pi$ à la dernière antenne) produit un *échange* des lobes, dans lequel le réseau de franges se superpose à lui-même. Si la rotation est progressive, le diagramme primaire est *balayé* par le diagramme d'interférence. Supposons maintenant la tension de sortie du récepteur appliquée à la grille d'un oscillographe cathodique de façon à produire une modulation d'intensité d'image, tandis que l'oscillographe est balayé synchroniquement. Sur l'oscillographe apparaîtra une image correspondant à une intégration par bandes (parallèles aux franges) de la distribution de brillance de la source.

Un tel déphasage progressif réalisé simultanément dans les deux alignements perpendiculaires d'un réseau synthétique (cf. Section 2, c)), et un balayage synchrone d'un oscillographe cathodique dans les deux dimensions produira une image de la source. Par ce moyen, il est possible d'envisager la production d'images du Soleil en succession rapide (du type télévision). Il est envisagé d'établir un tel instrument à la station de Humain de manière à produire plusieurs images solaires par minute sur $\lambda = 75$ cm. Malheureusement, la réalisation de déphaseurs progressifs pose encore des problèmes techniques importants.

E. J. BLUM [4] a examiné en 1951 la question des antennes rotatives. Un dipôle est placé excentré au foyer d'un paraboloïde et est mis en rotation autour de l'axe optique de manière à produire un faisceau d'antenne décrivant un cône. Il s'agit là, en fait, d'un système très usité dans la technique du radar (les premières applications datent de la guerre mondiale)

ainsi qu'en radiométéorologie (poursuite des ballons sondes) mais qui n'a reçu que peu d'applications en radioastronomie. Il est facile de voir qu'une source fine un peu distante de l'axe optique donnera une réponse modulée. La phase de cette réponse est en rapport avec la phase du mouvement de rotation et dépend de la position de la source. Une détection de phase donne directement la position de la source tandis que l'amplitude pour une modulation nulle donne son éclat. La méthode est applicable lorsque la zone céleste autour de la source est assez uniformément émissive, et cela constitue un inconvénient. Cependant, on bénéficie de l'avantage d'utiliser les flancs du lobe principal, qui sont inclinés: à titre d'exemple signalons qu'une expérience d'application de la méthode des hauteurs égales, faite à Humain en 1954, au passage du Soleil dans un lobe de 5° à mi-intensité sur 600 MHz a permis de déterminer radioastronomiquement le méridien avec une précision de $30''$ d'arc (erreur moyenne). Il est donc possible que tout n'ait pas été exploité à ce sujet.

g) Remarque sur les lobes secondaires. Des lobes secondaires, même peu importants, représentent un certain inconvénient et il est avantageux de les minimiser pour les raisons qui suivent:

1) ces lobes peuvent être dirigés vers des sources intenses de parasites terrestres (industriels, télévision, radars, etc.);

2) ils peuvent être dirigés vers le sol et influencer les mesures par suite de la radiation thermique du sol;

3) lorsque l'antenne est mobile, la présence de lobes secondaires importants dirigés vers le sol entraîne une modification de l'impédance d'antenne par effet d'antenne image; le diagramme arrière est surtout néfaste. Dans certains cas il est nécessaire de placer les antennes à une certaine distance au dessus du sol.

3. — La polarisation et le bruit radioélectrique solaire.

Une source étendue, située à grande distance, donne une onde électromagnétique dont le vecteur électrique est représentable par une intégrale de Fourier

$$\mathbf{E} = \int \boldsymbol{\Psi}(\mathbf{k}) \exp [2i\pi(\nu t - \mathbf{k}\mathbf{r})] d\mathbf{k},$$

où $\mathbf{k}$ est le vecteur de propagation ($|\mathbf{k}| = \nu/c$) ou vecteur des fréquences *spatiales* associé aux coordonnées comme la fréquence temporelle ν est associée au temps. Si cette source est le siège de processus aléatoires, le vecteur-amplitude $\boldsymbol{\Psi}(\mathbf{k})$ (spectre de Fourier) est une fonction aléatoire du temps. $d\mathbf{k}$ représente

un volume élémentaire de l'espace des $\mathbf{k}$ (dimensions m^{-3}) et l'on a évidemment

$$d\mathbf{k} = dk_x dk_y dk_z = \frac{v^2}{c^3} d\nu d\Omega,$$

$d\Omega$ représentant l'élément d'angle solide autour de la direction définie par le vecteur $\mathbf{k}$. Supposons la source relativement peu étendue et pointons une antenne relativement peu directive sur cette source. L'antenne isole certaines directions spatiales par son indicatrice tandis que le récepteur isole une bande de fréquences relativement étroite. A ce sujet, on peut considérer le radio-télescope comme un filtre de fréquences spatiales car l'intégration de Fourier est maintenant étendue à un certain domaine de l'espace de $\mathbf{k}$, de sorte que l'intégrale de Fourier devient

$$\mathbf{E} = \Psi(t) \exp [2i\pi(\nu_0 t - \mathbf{k}_0 \mathbf{r})],$$

ce qui représente un groupe d'ondes. $\Psi(t)$ est en général complexe et fonction aléatoire du temps; ν_0 représente la fréquence centrale du récepteur et $|\mathbf{k}_0| = \nu_0/c$.

Dans le plan d'onde perpendiculaire à $\mathbf{k}_0$, nous pouvons tracer deux directions de référence perpendiculaires X , Y . L'état de polarisation de l'onde est caractérisé par les paramètres de Stokes,

$$\overline{E_X E_X^*} = P, \quad \overline{E_Y E_Y^*} = Q, \quad \overline{E_X E_Y^*} = R + iS.$$

P et Q correspondent respectivement aux puissances moyennes des composantes polarisées suivant X et Y (rectilignes); R et S indiquent le degré de cohérence de ces composantes perpendiculaires.

Si l'amplitude Ψ était une constante complexe (vecteur complexe du plan d'onde), l'expression $\mathbf{E} = \Psi \exp [2i\pi\nu_0 t]$ représenterait un vecteur tournant dans le plan d'onde de manière à ce que son extrémité décrive une ellipse. La polarisation serait elliptique *pure* et l'on aurait alors $PQ = R^2 + S^2$. Les composantes X , Y de polarisation seraient cohérentes et le coefficient de corrélation $r = ((R^2 + S^2)/PQ)^{\frac{1}{2}}$ serait égal à l'unité. Comme Ψ est une fonction aléatoire du temps, seules les valeurs moyennes des carrés et produits ont une signification et sont mesurables. On voit qu'en fait les quantités à mesurer sont P , Q , R , S . Le coefficient de corrélation n'est plus égal à l'unité. La polarisation sera appelée ici *aléatoire*.

Pour une polarisation elliptique pure l'équation de l'ellipse de polarisation (ellipse décrite par l'extrémité de $\mathbf{E}$ dans le plan d'onde) est

$$QX^2 + PY^2 - 2RXY = S^2,$$

$S = 0$ correspond à une polarisation *rectiligne*; $P = Q$ et $R = 0$ correspondent à une polarisation *circulaire* dont le sens est défini par le signe de S . On fixe conventionnellement le sens comme suit: la polarisation est dite à droite lorsqu'un observateur tournant le dos à la source voit le vecteur électrique tourner dans le sens des aiguilles d'une montre. Lorsque les axes x, y sont orientés dans ce sens, la polarisation est à droite quand S est positif.

Les valeurs moyennes utilisées ici ont la signification suivante:

$$\bar{a} = \frac{1}{\tau} \int_{t_0}^{t_0 + \tau} a \, dt.$$

Ce sont encore des quantités fluctuantes mais on peut montrer, d'une manière assez générale, qu'elles sont beaucoup moins variables que $a(t)$. En fait l'écart quadratique moyen à leur valeur moyenne (pour les valeurs individuelles en t_0, t_1, t_2 , etc., successives) est proportionnel à $1/\sqrt{\tau}$.

Le rôle du circuit intégrateur dans la partie terminale du radiorécepteur astronomique est précisément de fournir la constante de temps τ définissant l'étendue de l'intervalle d'échantillonnage. On voit que les fluctuations des quantités enregistrées seront très faibles si τ est très grand. Il faut pourtant se garder d'exagérer dans ce sens car la radiation solaire, surtout sur ondes métriques, contient des sursauts rapides d'une durée de l'ordre de 0.1 s. Une constante de temps de l'ordre de 1 seconde noierait déjà des phénomènes intéressants.

La polarisation est au hasard lorsque $P = Q$ et $R = S = 0$. On peut montrer qu'une polarisation aléatoire (vecteur $\mathbf{E}$) est la somme d'une polarisation au hasard (vecteur $\mathbf{E}_h$) et d'une polarisation elliptique pure (vecteur $\mathbf{E}_e$) caractérisée par $P_e Q_e = E_e^2 = S_e^2$, les vecteurs $\mathbf{E}_h, \mathbf{E}_e$ étant *incohérents* (produits moyens nuls pour toutes les composantes).

Ordinairement les polarimètres radioastronomiques actuels mesurent la polarisation *circulaire*. Celle-ci est intéressante parce qu'elle révèle la présence de champs magnétiques. La polarisation *rectiligne* présente dans la radiation solaire est également intéressante. A notre connaissance, il n'existe pas d'instruments donnant directement P, Q, R, S . D'autre part, les exposés de A. D. FOKKER et H. TANAKA, dans le cycle de ces conférences, ont montré l'intérêt considérable des mesures de polarisation. Il semble bien que la polarimétrie radioastronomique soit un domaine insuffisamment explité. En tout cas, très peu de mesures de polarisation figurent dans les rapports d'ensemble (*Quarterly Bulletin of Solar Activity, CRPL-F Reports*).

Observons encore que si la radiation est polarisée au hasard ($P = Q, R$ et $S = 0$), une antenne ayant son axe électrique dirigé suivant X ne pourra mesurer que $\bar{E}_x \bar{E}_x^* = P$. Or la densité d'énergie du champ incident est égale à $2P$. Ceci explique le facteur $\frac{1}{2}$ qui figurera plus loin dans la théorie thermodynamique des antennes.

4. — Théorie thermodynamique des antennes.

Dans cette théorie, on admet l'approximation de l'optique géométrique: la radiation se propage sur des rayons infiniment déliés, se croisant en tout point sans donner d'interférences. Elle est polarisée au hasard. Un observateur en Q définit le champ de radiation qui y règne à la manière classique en astrophysique. Il place en Q une surface élémentaire dA dont la normale fait un angle θ avec la direction considérée de propagation (Fig. 10) et détermine la puissance traversant dA par unité de temps, du fait de la radiation de fréquence ν , $\nu + d\nu$ se propageant sur des directions intérieures à l'angle solide $d\Omega$. Cette puissance est

$$dP_\nu = I_\nu \, d\nu \cdot d\Omega \cdot dA \cos \theta$$

et I_ν est la *densité de flux par stéradian* ($\text{W} \cdot \text{m}^{-2} \cdot \text{Hz}^{-1} \cdot \text{sr}^{-1}$) pour les deux polarisations. Cette densité de flux par stéradian est également la *brillance apparente* de la source au point d'où provient la radiation.

A l'équilibre thermodynamique (par exemple dans une cavité fermée à l'équilibre dont les parois sont à une température uniforme constante T °K)

$$I_\nu = B_\nu(\tau) = \frac{2h\nu^3}{c^2} \frac{1}{\exp [\hbar\nu/kT] - 1},$$

loi de Planck bien connue ($h = 6.62 \cdot 10^{-27} \text{ W} \cdot \text{s}^2$; $k = 1.38 \cdot 10^{-23} \text{ W} \cdot \text{s} \cdot \text{deg}^{-1}$). Aux ondes longues de la radioastronomie, la formule de Planck se réduit à celle de Rayleigh-Jeans

$$B_\nu(T) = \frac{2kT\nu^2}{c^2},$$

avec une erreur relative de l'ordre de $\hbar\nu/2kT$.

L'erreur relative commise est de l'ordre de 1% pour $\lambda = 1 \text{ m}$ et $T = 1$ °K. Elle est tout à fait négligeable en radioastronomie solaire, même aux ondes millimétriques car les températures en jeu sont toujours supérieures à 10^3 °K.

Pour n'importe quelle source de radiation, on peut toujours définir une *température de brillance* T_b par la relation

$$I_\nu = \frac{2kT_b(\nu) \cdot \nu^2}{c^2},$$

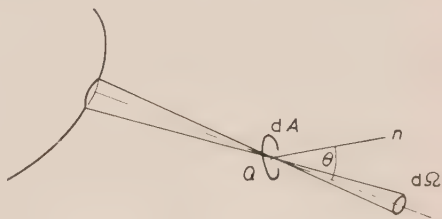


Fig. 10. — Définition de la densité de flux par stéradian ou brillance apparente.

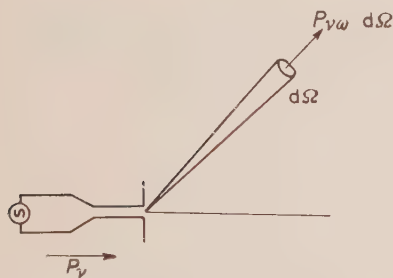
ce qui simplifie les idées. T_b , fonction de la fréquence, est un simple paramètre caractérisant la radiation en jeu.

Dans la théorie thermodynamique des antennes, nous aurons encore à tenir compte du théorème de Nyquist pour les réseaux résistifs portés à une certaine température. Considérons à cet effet une résistance R chauffée à une température T . Les électrons que contient cette résistance sont animés de vitesses thermiques et la dispersion de leurs vitesses crée aux bornes de la résistance une force électromotrice fluctuante. Cette tension fluctuante peut être analysée au sens de Fourier, ce qui conduit à en évaluer les composantes de fréquence. On démontre que, sous des conditions très générales, le spectre est uniforme et que, si l'on connecte la résistance à une autre résistance égale portée à 0 °K, elle y déversera une puissance par unité de fréquence

$$P_\nu = kT.$$

En résumé, la puissance maximum utilisable que peut fournir la résistance chauffée envisagée comme un générateur de bruit électrique est simplement égale à kT . Remarquons encore que la constante de Planck a été négligée dans le calcul. En fait ce résultat n'est vrai que dans le domaine radioélectrique.

a) *Antenne à l'émission.* A l'extrémité de la ligne de transmission conduisant à l'antenne, connectons un générateur délivrant une puissance P_ν par unité de fréquence (Fig. 11). Une puissance $P_{\nu\omega}$ par unité d'angle solide est alors rayonnée dans la direction $d\Omega$. Il est évident que du fait des pertes dans la ligne, dans le corps de l'antenne, etc., et par suite des ondes stationnaires qui accroissent les pertes [5],



$$\int P_{\nu\omega} d\Omega = \eta P_\nu,$$

avec $\eta \leq 1$ (intégrale étendue à toute la sphère). De plus posons

$$P_{\nu\omega} = \frac{1}{4\pi} G P_\nu.$$

Fig. 11. — L'aérien à l'émission.
Définition du gain d'antenne et du
facteur d'efficacité.

Alors

$$\int G d\Omega = 4\pi\eta.$$

G est le *gain d'antenne* dans la direction considérée; η est le *facteur d'efficacité* de l'aérien. Ce sont des fonctions de la fréquence. G est fonction de la direction.

L'indicatrice d'émission de l'antenne s'obtient en portant, sur chaque direction, à partir de l'antenne, une longueur proportionnelle à G .

b) *Antenne à la réception.* A l'extrémité de la ligne d'antenne connectons maintenant une résistance de charge R . L'antenne est exposée à une radiation non polarisée dont la densité de flux par stéradian est I_ν dans la direction $d\Omega$. La puissance dissipée dans R , du fait de la radiation tombant dans le cône $d\Omega$, est posée égale à

$$P_{\nu\omega} = \frac{1}{2} I_\nu \cdot A$$

(remarquons ici la présence du facteur $\frac{1}{2}$; à part ce facteur l'expression est analogue à la définition de la densité de flux).

A est la *section efficace d'absorption* de l'antenne réceptrice. C'est une fonction de la fréquence et de la direction. Il existe d'ailleurs une relation simple entre la section efficace A et le gain G .

c) *Relation entre G et A .* L'antenne, connectée à une résistance R , est placée dans une cavité fermée, à l'équilibre thermodynamique à la température T . Cette résistance chauffée se comporte comme un générateur et délivre une puissance kT , de sorte que

$$P_{\nu\omega(\text{émis})} = \frac{1}{4\pi} G \cdot kT.$$

D'autre part, l'antenne est exposée à une radiation isotrope non polarisée, et la résistance reçoit dans $d\Omega$ la puissance

$$P_{\nu\omega(\text{reçu})} = \frac{1}{2} \cdot \frac{2kT}{\lambda^2} \cdot A.$$

Mais à l'équilibre thermodynamique ces deux puissances sont égales (principe de l'équilibre de détail); ainsi

$$G = \frac{4\pi A}{\lambda^2}.$$

Ceci démontre que les indicatrices d'émission et de réception sont exactement les mêmes. Pour déterminer les propriétés directives d'une antenne à la réception, il suffit de la faire fonctionner à l'émission. De plus, si les pertes varient, l'indicatrice est simplement modifiée par homothétie puisque le facteur d'efficacité η est une propriété *globale* où la direction n'intervient pas. La meilleure indicatrice s'obtiendra dans les conditions d'*adaptation d'impédances* (égalité entre l'impédance d'antenne, l'impédance de charge et l'impédance

caractéristique de la ligne de transmission); cependant la directivité de l'antenne sera indépendante des conditions d'adaptation.

d) *Relation fondamentale de la radioastronomie; température d'antenne.* L'antenne, la ligne, et la résistance terminale sont à la température T_0 . L'aérien est exposé à une radiation dont la température de brillance est T_b . Quelle est la puissance globale reçue par la charge? On voit qu'il s'agit du problème fondamental de la radioastronomie parce qu'il consiste à définir la puissance effectivement dissipée dans l'impédance d'entrée du récepteur (c.à.d. la puissance d'entrée), dont une mesure est fournie par la tension ou la puissance de sortie. Connaissant cette puissance de sortie, on pourra définir T_b c'est à dire les caractéristiques radiatives de la source. Le calcul s'effectue très simplement comme suit.

L'antenne émet une puissance par unité d'angle solide

$$P_{\nu\omega(\text{émis})} = \frac{1}{4\pi} G \cdot kT_0,$$

elle reçoit une puissance par unité d'angle solide

$$P_{\nu\omega(\text{reçu})} = \frac{1}{2} \cdot \frac{2kT_b}{\lambda^2} \cdot \frac{\lambda^2 G}{4\pi},$$

laquelle est dissipée dans la charge. Il n'y a pas équilibre thermodynamique mais seulement équilibre global; en désignant par P_ν la puissance globale reçue par la charge et en tenant compte du fait que la puissance globale fournie par la charge est kT_0 ,

$$P_\nu - kT_0 = \int P_{\nu\omega(\text{reçu})} d\Omega - \int P_{\nu\omega(\text{émis})} d\Omega.$$

Ainsi

$$P_\nu = k \left\{ T_0 + \frac{1}{4\pi} \int (T_b - T_0) G d\Omega \right\},$$

ou bien encore en posant $P_\nu = kT_a$

$$T_a - T_0 = \frac{1}{4\pi} \int (T_b - T_0) G d\Omega.$$

T_a est la *température apparente d'antenne*. C'est la température à laquelle il faudrait porter un réseau dissipatif, d'impédance égale à l'impédance de radiation de l'antenne, et connecté à sa place à la ligne de transmission, pour produire la même déviation de l'appareil de mesure à la sortie.

Ceci permet la *calibration* du récepteur. On remplace l'antenne par une résistance équivalente. On porte cette résistance à diverses températures physiques T_a . On inscrit ainsi une échelle de température sur l'appareil de mesure. L'antenne est ensuite remise en place et dirigée vers la source. L'appareil de mesure dévie et indique une certaine température T_a . Celle-ci dépend de T_b , température de brillance de la source, par une expression intégrale portant sur le gain d'antenne. T_0 est supposée connue; elle est d'ailleurs constante. La résistance chauffée de calibration peut toujours être remplacée par une source équivalente de bruit.

e) *Température équivalente du disque solaire*. Supposons le disque solaire très petit par rapport à l'ouverture angulaire du faisceau d'antenne, et l'antenne pointée, au gain maximum G_m sur le centre du disque. On observe une certaine température T_a . On imagine alors que toute la radiation provient d'un disque uniforme à la température de brillance T_s . Cette température est donnée par

$$T_a = T_s \frac{G_m}{185\,000} + (1 - \eta)T_0,$$

puisque le disque solaire soustend un angle solide $4\pi/185\,000$ stéradian. Par exemple $G_m = 18.5$, $T_a = 300$ °K, $T_s = 3 \cdot 10^6$ °K. T_s est la température équivalente du disque. C'est celle que devrait avoir un corps noir de dimensions apparentes égales à celles du disque solaire pour produire le même flux à la fréquence considérée.

Si le lobe était suffisamment étroit pour que T_b , la température de brillance de la source, soit constante dans le diagramme, on aurait eu

$$T_a = \eta T_b + (1 - \eta)T_0,$$

soit $T_a = T_b$ pour $\eta = 1$. L'antenne déterminerait alors directement la température de brillance locale.

Nous n'insistons pas ici sur l'influence du facteur d'efficacité. Mentionnons seulement que son rôle est néfaste quand T_0 est susceptible de variations (par exemple au cours d'éclipses solaires). L'influence des pertes sur la précision des mesures a été envisagée dans [5]. On y a traité également le cas des désadaptations d'impédances [6].

f) *Une méthode simple pour la détermination du gain d'antenne*. Il est facile de déterminer la forme du diagramme de directivité en faisant passer une source fine dans le faisceau d'antenne. Posons

$$G = G_m \cdot f(\theta, \varphi),$$

θ et φ désignant deux angles de repérage par rapport à la géométrie de l'antenne, et $f(0, 0) = 1$. Les passages de la source à différentes inclinaisons fournissent $f(\theta, \varphi)$, valeur relative du gain.

La détermination du gain absolu est toujours délicate. Une méthode simple, la méthode « du bois de sapins », est souvent utilisée. Elle repose sur le fait qu'une forêt de sapins couvrant le sol constitue un excellent corps noir aux fréquences radioélectriques, mais il est bien évident qu'une telle couverture n'est pas indispensable.

Dirigeons l'antenne vers l'horizon, de manière à ce que son diagramme soit exactement bissecté par le plan du sol. Soit T_s la température du sol et T_c celle du ciel. Dans la formule fondamentale, il faut identifier T_b à T_s dans la demi-sphère inférieure et à T_c dans la demi-sphère supérieure. Si ces températures de brillance sont constantes sur toute l'étendue des domaines d'intégration (ce qui n'est vrai qu'en moyenne) on a

$$T_a - T_0 = \frac{1}{2}\eta T_s + \frac{1}{2}\eta T_c - \eta T_0.$$

Ayant mesuré T_a et connaissant T_0 , T_s et T_c on en déduit le facteur d'efficacité

$$\eta = (T_a - T_0) / \left(\frac{T_s + T_c}{2} - T_0 \right).$$

Pour déterminer ensuite le gain maximum il suffit de tenir compte de ce que

$$\int G d\Omega = 4\pi\eta = G_m \int f d\Omega.$$

L'intégrale $\int f d\Omega$ peut être évaluée graphiquement. La température du ciel T_c est connue à partir des mesures galactiques (cartes d'isophotes radioélectriques). Généralement, une température moyenne est adoptée. La méthode peut cependant être perfectionnée en tenant mieux compte de la distribution de brillance du ciel, par exemple en adoptant des domaines séparés à diverses températures T_s . Néanmoins, la méthode du bois de sapins ne s'applique qu'aux antennes orientables. La détermination absolue des températures T_s est encore délicate. Elle s'effectue au moyen d'antennes étalon de gain (par exemple des cornets, rigoureusement calculables).

5. - L'aérien envisagé comme filtre linéaire de fréquences spatiales.

Considérons une infinité de mesures faites en dirigeant successivement l'antenne vers chacun des points d'une source étendue. Pour simplifier la question, supposons la source assez étroite (ce qui est réalisé pour le Soleil) pour qu'on puisse identifier sur toute son étendue la sphère céleste à son plan

tangent (Fig. 12). Dans ce plan tangent, nous prendrons des coordonnées cartésiennes *angulaires* u, v en graduant les axes de manière que $du \cdot dv = (1/4\pi) d\Omega$. La formule fondamentale établie à la Section 4 devient

$$T_a(\alpha, \beta) = \iint G(x, y) T_b(x + \alpha, y + \beta) dx dy + (1 - \eta)T_0,$$

les limites d'intégration pouvant être prises infinies.

Ainsi, $T_b(u, v)$ peut en principe être déduite de $T_a(u, v)$ grâce à une équation intégrale. Celle-ci a d'ailleurs une forme très simple car elle contient le *produit de corrélation* $f * g$ de deux fonctions; nous la noterons:

$$T_a = G * T_b + (1 - \eta)T_0.$$

Les propriétés spectrales qui s'en déduisent sont intéressantes. Soient en effet les transformées de Fourier

$$\tau_a(p, q) = F(T_a) = \iint T_a(u, v) \exp[-2i\pi(pu + qv)] \cdot du \cdot dv,$$

$$\tau_b(p, q) = F(T_b) = \iint T_b(u, v) \exp[-2i\pi(pu + qv)] \cdot du \cdot dv,$$

et posons ensuite

$$\gamma(p, q) = F^{-1}(G) = \iint G(u, v) \exp[+2i\pi(pu + qv)] \cdot du \cdot dv.$$

En prenant la transformée de Fourier du second membre de l'équation intégrale, on vérifie que

$$\tau_a = \gamma \cdot \tau_b + (1 - \eta)T_0 \cdot \delta(p, q),$$

où δ désigne la fonction de Dirac. Dans l'espace des *fréquences spatiales* p, q associées aux coordonnées u, v , le produit de corrélation se résume à un produit ordinaire des fonctions spectrales tandis qu'une singularité apparaît à l'origine du fait que le terme $(1 - \eta)T_0$ est une constante indépendante des coordonnées. Cette singularité n'est pas gênante; elle disparaît d'ailleurs lorsque le facteur d'efficacité vaut l'unité. Le premier terme est plus intéressant car c'est celui qu'on obtient dans la théorie des filtres linéaires électriques de fré-

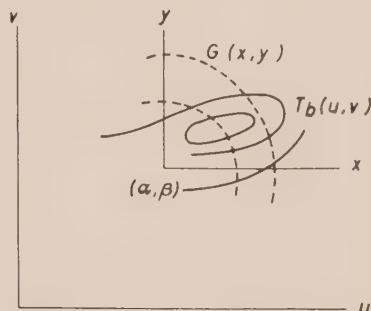


Fig. 12. — L'aérien envisagé comme un filtre linéaire de fréquences spatiales. Dans le plan (u, v) , distribution de brillance $T_b(u, v)$. Dans le système d'axes (x, y) , gain d'antenne $G(x, y)$. Formation de l'équation intégrale.

quence. Il montre qu'en première approximation, l'antenne peut être envisagée comme un *filtre linéaire de fréquences spatiales*.

L'idéal consisterait évidemment à obtenir $\tau_a = \tau_b$ car alors $T_a = T_b$ (la mesure fournirait toutes les composantes de fréquences spatiales de la source). Dans ce cas, $\gamma = 1$ c'est à dire $G(x, y) = \delta(x, y)$; le diagramme d'antenne serait constitué d'un seul faisceau infiniment délié.

Tout autre faisceau donne une « image brouillée ». Soit en effet $G(x, y) \sim \exp [-(x^2 + y^2)]/\sigma^2$; dans ce cas $\gamma(u, v) \sim \exp [-(u^2 + v^2)] \cdot \sigma^2$. La distribution spectrale pour l'aérien occupe un intervalle de fréquences spatiales d'autant *plus étroit* que le faisceau d'antenne est *plus large*. En comparant τ_a et τ_b , on voit que les composantes de hautes fréquences spatiales sont défavorisées par rapport aux composantes de basses fréquences.

En pratique, le gain d'antenne s'annule toujours identiquement hors d'un angle solide déterminé, ou bien n'est pas utilisé hors d'un angle solide déterminé (ne serait-ce que par l'effet du sol). Cela indique que le spectre γ de l'aérien devient identiquement nul au dehors d'un intervalle déterminé de fréquences spatiales. Dans ces conditions, on voit, en comparant τ_a et τ_b , que certaines composantes de hautes fréquences spatiales sont perdues irrémédiablement. En fait, la mesure est toujours accompagnée d'une perte d'informations, et cette perte est d'autant plus grande que l'antenne est moins directive. Ceci rend illusoire le problème de la restitution complète d'une distribution de brillance à partir des températures mesurées et de la connaissance du gain d'antenne. Néanmoins, une certaine amélioration peut être obtenue par la méthode suivante.

Tout d'abord

$$T_b(u, v) = F^{-1}(T_b) = \iint \frac{\tau_a(p, q)}{\gamma(p, q)} \exp [2i\pi(pu - qv)] dp dq + \frac{(\eta - 1)T_0}{\gamma(0, 0)}.$$

Ici $\gamma(0, 0)$ est simplement $\iint G du \cdot dv = \eta$ de sorte que le dernier terme devient égal à $((\eta - 1)/\eta)T_0$. La correction est possible dès que l'on connaît T_0 et le facteur d'efficacité. Elle est généralement de faible importance pour les mesures radiosolaires.

Le traitement du premier terme est plus délicat, parce que les dimensions finies des antennes imposent toujours à $\gamma(p, q)$ de s'annuler au moins sur un intervalle fini de l'espace (p, q) . Un intervalle de mesure nulle n'aurait aucune importance parce que sa contribution à l'intégrale de Fourier est nulle, mais un tel intervalle fini a une importance désastreuse parce que le rapport τ_a/γ y est *indéterminé*. (τ_a et γ s'annulant en même temps sur un intervalle excluant l'origine $(0, 0)$ du plan (p, q)). Il est difficile de lever cette indétermination; néanmoins, en écrivant

$$\frac{\tau_a}{\gamma} = \frac{\tau_a}{1 - (1 - \gamma)} = \tau_a \sum_n a_n (1 - \gamma)^n,$$

et en limitant la série à N termes on obtient une expression approchée au moyen de laquelle une certaine correction des adoucissements provoqués par l'antenne (effets de lobe) est obtenue. Dans une certaine mesure, la méthode est comparable à celle de la correction du profil instrumental dans les mesures spectrographiques optiques.

On voit ainsi que le problème de la restitution des distributions réelles de brillance en radioastronomie est excessivement délicat. On pourrait s'imaginer qu'il suffirait de connaître parfaitement les propriétés de l'antenne pour pouvoir déduire une image parfaite d'observations effectuées à l'aide d'un instrument imparfait, mais certains arguments mathématiques s'opposent à une correction complète. Il est en effet impossible de retrouver les composantes de haute fréquence arrêtées par l'antenne. La seule solution est de permettre le passage de ces composantes, soit en affinant le faisceau d'antenne ce qui élargit son spectre, soit en ajoutant artificiellement des domaines spectraux au moyen d'aériens auxiliaires. Il n'est pas nécessaire, en effet, que la « bande passante » de l'antenne soit d'un seul tenant; elle peut par exemple consister en un ensemble de bandes séparées.

6. — Exemple de spectre d'aérien; radiation d'une ouverture.

Considérons une fenêtre percée dans un écran opaque (plan x, y) et illuminée par une onde plane monochromatique provenant d'une source à l'infini dans la direction négative de l'axe z . Limitons nous au problème scalaire de Kirchhoff (voir également l'article de G. TORALDO [7]). On a l'équation de propagation

$$\Delta u + k^2 u = 0 \quad \left(k = \frac{2\pi}{\lambda} \right)$$

et la formule de Kirchhoff bien connue

$$u_P = \frac{1}{4\pi} \int (u \psi_n - \psi u_n) dS,$$

u_P désignant le champ en un point P de l'espace (situé dans la région $z > 0$), $\psi = (1/r) \exp[-ikr]$, l'indice n représentant une dérivation suivant la normale à la surface de l'ouverture, et la sommation étant étendue à toute l'ouverture. Dans le cas vectoriel, cette formule est remplacée par celle de Kottler, mais les résultats à grande distance (zone de Fraunhofer) sont approximativement les mêmes dans le voisinage de l'axe z excepté que la polarisation n'est pas envisagée ici. Si l'onde incidente est $u = a(x, y) \exp[-ikz]$, le champ à grande

distance R de l'origine est donné par

$$u_P(x, y, z) = \frac{ik}{4\pi} \frac{\exp[-ikR]}{R} \int_S a(\xi, \eta) \exp[ik(l\xi + m\eta)] d\xi d\eta,$$

ξ, η désignant les coordonnées d'un point de la fenêtre plane, et l, m étant les cosinus directeurs de la direction envisagée, par rapport aux axes x, y .

La puissance rayonnée est $u \cdot u^*$. On a

$$(u \cdot u^*)_P = \frac{k^2}{16\pi^2 R^2} \int_S \varrho(\alpha, \beta) \exp[-ik(\alpha l + \beta m)] d\alpha d\beta,$$

où

$$\varrho(\alpha, \beta) = \int_S a(\xi, \eta) a^*(\xi + \alpha, \eta + \beta) d\xi d\eta.$$

Cette intégrale est étendue à l'ouverture. Celle de la formule précédente est étendue au domaine des distances mutuelles ($\alpha = \xi' - \xi, \beta = \eta' - \eta$) entre les points de l'ouverture.

On voit ainsi: 1) que ϱ est la fonction de corrélation des champs sur l'ouverture, 2) que le diagramme d'antenne est donné par une intégrale de Fourier; en ce sens $k\alpha$ et $k\beta$ sont les fréquences spatiales.

Ici le spectre de l'aérien est précisément la fonction de corrélation ϱ .

L'intégrale de la formule précédente n'aura de valeur sensible que dans le domaine (α, β) où les champs sur l'ouverture sont corrélés. En particulier, si l'ouverture consiste en deux régions séparées avec des champs non corrélés d'une région à l'autre, nous n'aurons aucune contribution supplémentaire à celle que nous obtiendrions si nous considérions chaque ouverture séparément.

Ceci permet encore d'apercevoir les limitations du pouvoir résolvant d'un interféromètre à grande base (par exemple à deux antennes) en présence de scintillation ionosphérique. Du fait de la scintillation due aux irrégularités de l'ionosphère, les champs provenant d'une source ponctuelle cessent d'être corrélés à une certaine distance sur le sol. Nous basant sur le principe de réciprocité, nous voyons qu'il est inutile d'écarter les deux antennes d'un interféromètre, ou d'accroître la longueur de la base, au delà de la « distance de corrélation ».

7. — Types d'antennes utilisées en radioastronomie.

L'antenne constituant un élément de transition entre la ligne de transmission et le vide où se propagent les ondes électromagnétiques, il est évident que la structure de l'antenne doit être appropriée à celle de la ligne.

Aux ondes métriques les lignes de transmission bifilaires (deux conducteurs parallèles) ou coaxiales (deux cylindres de même axe) sont utilisées. Aux ondes décimétriques les lignes coaxiales sont meilleures mais les lignes bifilaires sont encore utilisées; cependant, ces lignes rayonnent et des pertes par radiation s'introduisent. Aux ondes centimétriques on peut encore à la rigueur utiliser les lignes coaxiales mais les pertes diélectriques ou ohmiques deviennent rapidement prohibitives; il est préférable d'utiliser les guides d'ondes (tuyaux creux à section rectangulaire, rarement circulaire). Les lignes à ondes superficielles (lignes de Goubau) peuvent présenter un intérêt mais elles n'ont pas encore été utilisées à notre connaissance dans les applications radioastronomiques. Dans le cas de lignes bifilaires ou coaxiales, les éléments sensibles employés dérivent du *dipôle* demi-onde. Dans le cas du guide d'onde, ils consistent en *cornets*, parfois en dipôles convenablement disposés; mais dans ce dernier cas on peut considérer qu'une transition élémentaire guide-coaxial a été interposée.

Un dipôle demi-onde est un élément symétrique; pour l'associer à une ligne coaxiale asymétrique il est nécessaire d'interposer un dispositif de symétrisation. Pour la description de tels dispositifs, cf. [8], [9]. Alimenté par le centre, le dipôle demi-onde à la résonance a une basse impédance (73Ω pour un dipôle mince, 64Ω pour un diamètre de $10^{-1} \lambda$, inférieure à 50Ω pour un diamètre de l'ordre de $10^{-2} \lambda$); alimenté par les bouts, l'impédance est très élevée (plusieurs milliers d'ohms). La longueur résonnante ou longueur électrique est 0.47λ pour un diamètre de $2 \cdot 10^{-3} \lambda$. Le lobe présente une symétrie axiale par rapport au dipôle; le gain maximum est 1.64; l'angle d'ouverture à mi puissance vaut $78^\circ.2$.

Le cornet est un élément exactement calculable, pouvant servir comme étalon de gain. Pour sa description, cf. [10].

a) *Introduction d'éléments passifs réels ou virtuels.* L'indicatrice d'un dipôle n'est généralement pas suffisante pour l'usage radioastronomique; son gain est trop faible. L'indicatrice et le gain peuvent être améliorés par l'introduction d'éléments passifs réels (dipôles passifs parallèles, placés à une certaine distance du dipôle actif, fonctionnant par diffraction). Suivant la position, l'indicatrice est projetée vers le dipôle actif ou à l'opposé de celui-ci (cf. [11]). Ajouter trop d'éléments passifs rend le système critique; en fait les éléments Yagi (comprenant par exemple deux directeurs et un réflecteur [9]) fonctionnent sur une bande étroite de fréquence. Un dipôle passif est directeur lorsque, placé devant le dipôle dans la région d'où les ondes viennent, il dirige l'indicatrice vers la source; il est réflecteur lorsqu'il dirige l'indicatrice vers la source et lorsqu'il est placé derrière le dipôle actif.

Des éléments passifs virtuels peuvent également être utilisés. En plaçant parallèlement au dipôle actif un plan conducteur on crée à l'arrière de ce plan un dipôle virtuel excité en opposition de phase, ou dipôle image. Un système



Fig. 13. — Antenne dipôle-disque à fente illuminant un paraboloïde Würzburg de 7.5 m fonctionnant sur 600 MHz (Station radioastronomique de Humain-Rochefort).

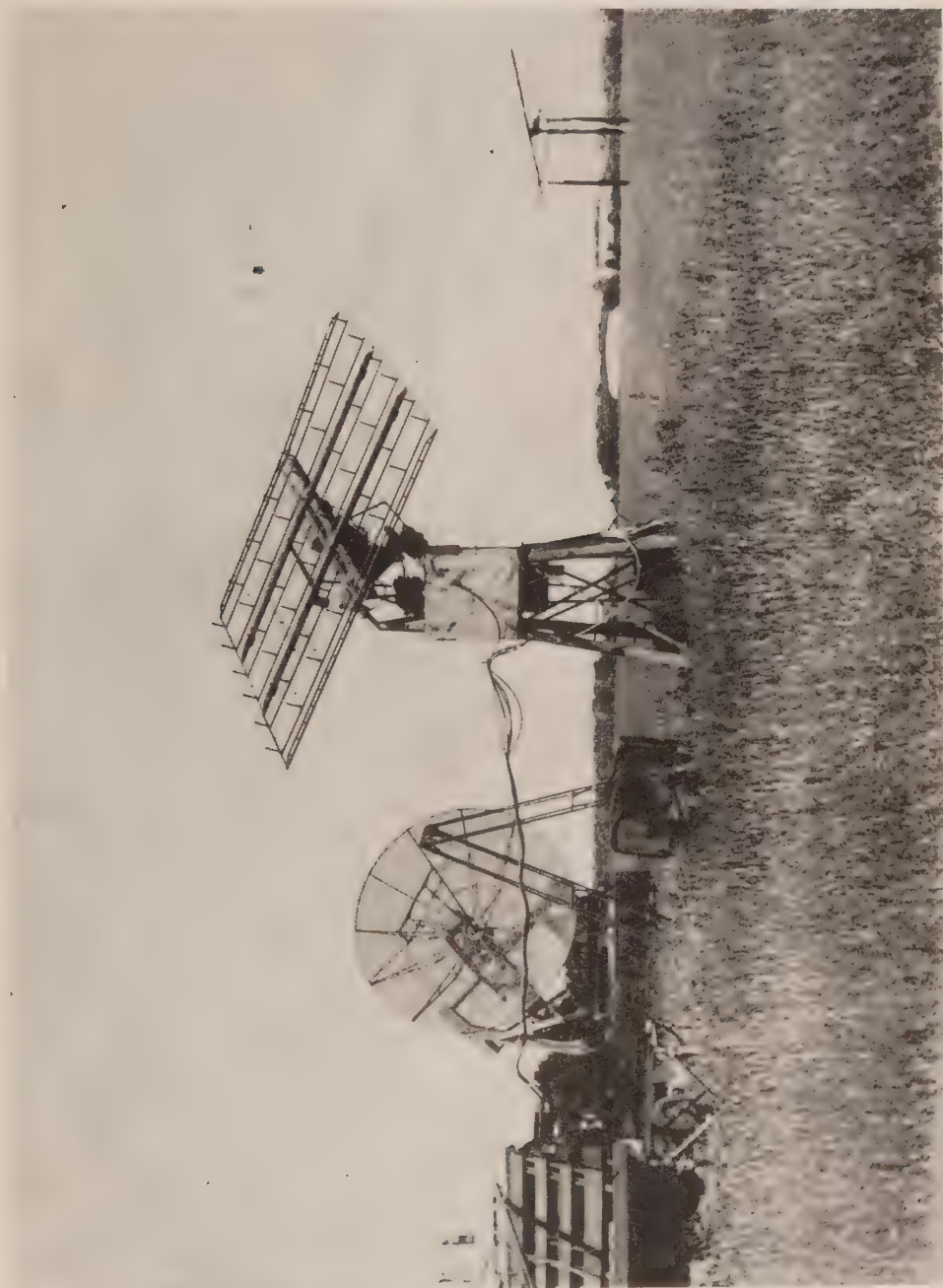


Fig. 14. Un réseau à radiation transversale d'antennes dipôles demi-onde (Cornell University, Ithaca, N. Y.).

de ce type est le dipôle disque à fente, qui donne de bons résultats (diagramme exactement axial) en particulier pour l'illumination d'un paraboloïde.

Voir Fig. 13 et [12].

b) *Radiation d'ouverture, réseaux et paraboloïdes.* On peut combiner des dipôles actifs suivant des lignes, des colonnes, en couvrir des surfaces planes; la connexion peut être faite de beaucoup de manières possible. Le calcul de tels antennes est assez facile au moyen a) du principe de superposition (il suffit d'ajouter les contributions des divers champs d'onde $E = \sum E_i$, puis de calculer EE^*), b) du principe de la multiplication des diagrammes (cf. [13]).

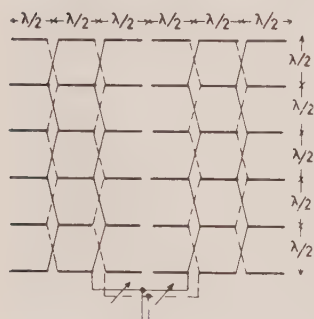


Fig. 15. — Connexion en phase dans un réseau de dipôles demi-onde (réseau à radiation transversale).

Un réseau de dipôles du type représenté par la Fig. 14 matérialise en fait une portion d'onde plane où les vecteurs électriques sont distribués uniformément en phase si la connexion est faite suivant la Fig. 15. Le gain maximum dans la direction perpendiculaire au plan du réseau est approximativement $4\pi ab/\lambda^2$ (a et b = longueur des côtés). Suivant l'excitation des dipôles d'une ligne on a un réseau à radiation longitudinale (end-fire) ou transversale (broad-side, c'est à dire suivant la normale à l'alignement). Les réseaux à radiation transversale sont souvent utilisés; la radiation

arrière en est généralement supprimée par un écran placé derrière les dipôles à $\frac{1}{4}$ longueur d'onde.

Souvent les antennes consistent en paraboloïdes ayant au foyer un dipôle ou un cornet. La radiation du dispositif est encore celle d'une ouverture, celle de la « bouche » du paraboloïde. Le gain maximum s'obtient pour une ouverture plane illuminée en phase. Il est donc intéressant que la distance focale ne soit ni trop grande ni trop petite; une bonne moyenne est $F = 1.5$ fois la profondeur du miroir. Approximativement, pour un paraboloïde, $G_m = 4.5 D^2/\lambda^2$ et $\theta_1 = 60^\circ \lambda/D$ (D = diamètre). Notons qu'il est pratiquement impossible de réaliser les conditions optima. Le problème des aberrations du dispositif (paraxiales, coma, astigmatisme, lobes secondaires, etc.) a été traité extensivement étant donné l'emploi des paraboloïdes dans la technique du radar et des télécommunications sur microondes.

c) *Aériens pour microondes.* Les problèmes posés pour ces aériens sont intermédiaires entre ceux de la radioélectricité et de l'optique. Les paraboloïdes pour microondes sont illuminés soit par un dipôle, soit par un cornet, soit par un guide d'onde fendu, soit par une antenne diélectrique, etc. Toutes les méthodes connues et appliquées en technologie n'ont pas encore été utilisées en radioastronomie. Des lentilles diélectriques, métalliques, de Fresnel,

zonées, en doublet achromatique, etc., sont également utilisables. Voir [12, 13, 14].

Citons encore les guides à fentes fonctionnant sur la base du principe de Babinet (réciprocité entre fente demi-onde et dipôle demi-onde), les antennes cigares (réalisation d'un indice de réfraction périodiquement variable sur l'axe prolongé d'une ligne coaxiale, au moyen de rondelles métalliques enfilées), les antennes diélectriques, etc.

d) *Antennes à ondes progressives*. L'antenne rhombique appartient à ce type (Fig. 16). Elle est peu critique donc à bande large; son impédance est pratiquement indépendante de la fréquence sur un large intervalle (exemple, 100 à 200 MHz) ce qui la rend utile en radiospectroscopie. Elle est facile à réaliser, et intéressante aux ondes longues. Ses lobes secondaires sont malheureusement importants.

Un aérien d'un grand intérêt est l'hélicoïde (Fig. 17). On peut combiner des hélicoïdes en réseaux. Quand la radiation est longitudinale (gain maximum sur l'axe de l'hélice) l'aérien est polarisé *circulairement* ce qui présente un certain intérêt pour la construction de polarimètres. Le gain et l'angle d'ouverture sont donnés par

$$G_m = 10 \log \left(15 \frac{e^2 N S}{\lambda^3} \right); \quad \theta_{\frac{1}{2}} = 52^\circ \left(\frac{e^2 N S}{\lambda^3} \right)^{\frac{1}{2}}.$$

L'adaptation à un coaxial est aisée (Fig. 17).

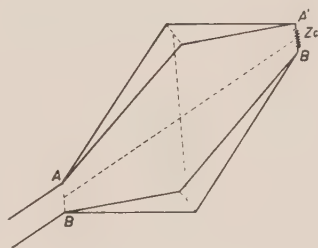


Fig. 16. — Une antenne à ondes progressives: l'antenne rhombique. Ce système se caractérise par une assez bonne directivité et une large indépendance des conditions d'adaptation d'impédances. Lobes secondaires importants.

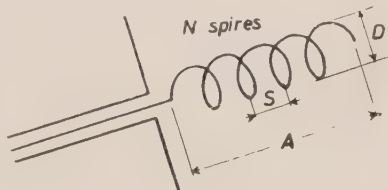


Fig. 17. — Type d'antenne hélicoïdale utilisable sur ondes métriques et décimétriques. Remarquer le réflecteur et la transition vers le câble coaxial.

II. - Le Radiomètre.

1. - Description générale du récepteur radioastronomique.

Le récepteur radioastronomique est généralement du type superhétérodyne (Fig. 18) et comprend *au moins un* changement de fréquence. L'utilisation d'un tel dispositif est justifiée par plusieurs raisons:

a) il est généralement plus facile d'amplifier sans bruit de fond les fréquences moyennes (exemple, 30 MHz) que les fréquences élevées (exemple 600 MHz);

b) les amplifications demandées sont considérables (exemple, 120 db) et ne pourraient être réalisées sous fréquence unique sans que le récepteur ne se

mette à osciller. Notons que même une trace d'accrochage est désastreuse pour le bruit de fond.

Le facteur d'amplification en volts d'un tel récepteur doit être en effet de l'ordre de 1 million de fois.

Le récepteur comprendra donc le plus généralement: a) un amplificateur des radiofréquences; b) un mélangeur couplé à un oscillateur local où s'effectue le changement de fréquence par battements; un tel mélangeur est soit un amplificateur à gain modulé soit un

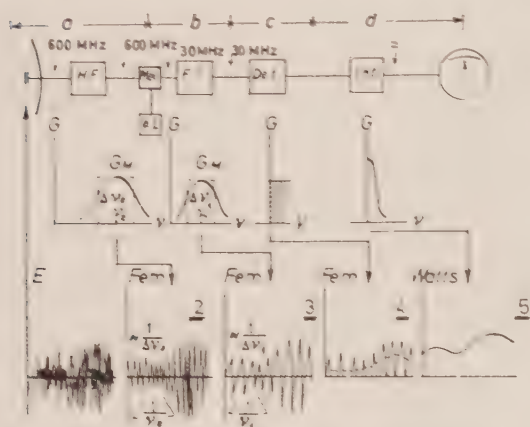


Fig. 18. - Schema d'un récepteur superhétérodyne.
Effet des différentes sections sur le signal.

élément non linéaire conduit par cette oscillation locale; c) un amplificateur de fréquence intermédiaire; d) un détecteur, élément non linéaire où les oscillations sont redressées; e) un intégrateur adoucissant l'enveloppe obtenue; f) un enregistreur, ou tout autre dispositif de mesure de tensions continues où les variations de cette enveloppe sont mises en évidence.

2. - Cas du récepteur parfait.

Un récepteur sera dit parfait s'il ne présente pas de bruit de fond interne. Il est caractérisé essentiellement par:

- a) sa courbe de gain en volt;
- b) sa courbe de saturation.

Pour définir le gain en volt, on connecte à l'entrée du récepteur un générateur sinusoïdal étalonné et l'on mesure le rapport V_s/V_e entre la tension de sortie après intégration, et l'amplitude de la tension sinusoïdale à

l'entrée, ceci en fonction de la fréquence. La courbe de saturation s'obtient de la même manière, mais en faisant varier la tension d'entrée, ceci à fréquence fixe (Fig. 19).

a) $G_v = (V \text{ sortie}) / (V \text{ entrée})$ est le facteur d'amplification en volt.

b) Conventionnellement $G_p = G_v^2$ est le gain de puissance.

c) Exprimé en décibels, le gain de puissance est $G_{db} = 10 \log G_p$

d) La saturation des récepteurs radioastronomiques commence déjà lorsqu'on applique quelques microvolt à l'entrée (ou quelques dizaine de μV suivant la sensibilité) à la fréquence centrale ν_0 . Cette saturation provient sur tout des étages finaux, spécialement du détecteur.

e) La bande passante est $B_{(MHz)}$ = surface de la courbe G_v / gain maximum $G_{v,M}$ (noise bandwidth). On utilise aussi la largeur de bande ν_0 à mipuissance mais les deux définitions sont pratiquement équivalentes étant donné que l'optimum consiste à obtenir des flancs suffisamment raides et un sommet suffisamment horizontal. La bande optimum serait rectangulaire.

f) Une pareille bande passante peut être tracée pour chaque étage linéaire du dispositif (voir Fig. 18).

Ceci nous permet d'analyser l'effet du signal d'entrée sur les différents étages du récepteur.

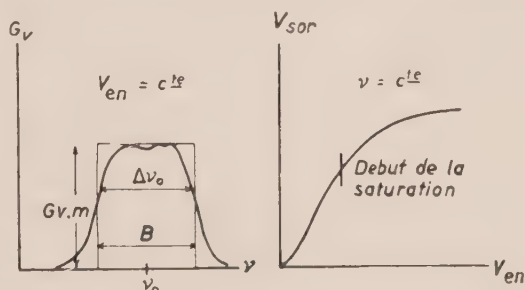


Fig. 19. — Bande passante et courbe de saturation d'un récepteur.

3. - Réaction d'un récepteur parfait en présence d'un bruit électrique à l'entrée.

Nous avons vu précédemment que le signal d'antenne est une fonction aléatoire du temps. Ceci résulte du fait que la source naturelle (en l'occurrence le Soleil) est une source à spectre continu, examinée sur un intervalle spectral correspondant à la bande d'acceptance du récepteur. En fait, la tension électrique au premier étage est une tension fluctuante. L'effet est synthétisé par la Fig. 18.

Comme les bandes d'acceptance ont une certaine largeur, le signal de sortie est une tension ou un courant fluctuants. La fluctuation est évidemment beaucoup moins importante que celle de la tension à l'entrée. Il faut distinguer ici l'effet de l'*intégrateur* et celui de la *bande passante*.

1) *Effet de l'intégrateur*. Un tel intégrateur peut être constitué par un circuit RC. Si les tensions à l'entrée V et à la sortie V' sont représentées par des intégrales de Fourier:

$$V = \int \varphi(\omega) \exp[i\omega t] d\omega ; \quad V' = \int \psi(\omega) \exp[i\omega t] d\omega ,$$

les spectres vérifient la relation

$$\psi\psi^* = \varphi\varphi^* \frac{1}{1 + (\omega CR)^2}$$

et l'on montre qu'approximativement, l'effet est celui d'une moyenne mobile sur V

$$\bar{V} = \frac{1}{\tau} \int_{t_0}^{t_0 + \tau} V(t) dt ,$$

où $\tau = RC$. Il s'agit encore d'une fonction aléatoire mais la fluctuation est, sous des conditions très générales, donnée par

$$\sqrt{(V - \bar{V})^2} = \frac{\bar{V}}{\sqrt{\tau}}$$

dans le cas d'un processus poissonnien.

2) *Effet de la bande passante*. Un signal aléatoire appliqué à un circuit résonnant amorti, de bande B , donnera lieu à un courant fluctuant dont la fluctuation, sous des conditions très générales, est donnée par

$$\sqrt{(I - \bar{I})^2} \simeq \frac{\bar{I}}{\sqrt{B}} .$$

En résumé, la puissance de sortie sera une fonction aléatoire qui, pour un récepteur parfait, aura une fluctuation donnée par

$$\sqrt{(P - \bar{P})^2} = \frac{\bar{P}}{\sqrt{B\tau}} .$$

Soit, par exemple, un récepteur parfait connecté à une antenne à la température T_a . Dans ce cas (Fig. 20) une puissance $kT_a B$ est injectée à l'entrée: une puissance $GkT_a B$ est recueillie à la sortie. L'erreur quadratique moyenne sur la puissance de sortie, pour ce récepteur parfait est

$$\frac{GkT_a B}{\sqrt{B\tau}} \quad \text{soit} \quad \Delta T_a = \frac{T_a}{\sqrt{B\tau}}.$$

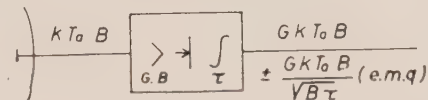


Fig. 20. — Fluctuations à la sortie d'un récepteur parfait (sans bruit de fond).

C'est une erreur d'origine naturelle.

contre laquelle nous ne pouvons rien;

elle résulte du caractère aléatoire de la tension d'entrée. Si $T_a = 300^\circ \text{K}$, $B = 1 \text{ MHz}$, $\tau = 1 \text{ s}$, alors l'erreur quadratique moyenne sur la température d'antenne est

$$\Delta T_a = 0.3^\circ \text{K} \quad \text{soit} \quad 1\%.$$

Si nous avons pris $B = 0.1 \text{ MHz}$, et $\tau = 0.1 \text{ s}$, nous aurions obtenu une erreur relative moyenne de l'ordre de 1%. Pour des mesures d'éclipses radio-solaires, cette erreur est nettement trop élevée. En conclusion, il y a lieu: 1) d'accroître la largeur de bande, 2) d'accroître la constante de temps de sortie.

Ceci entraîne cependant certains inconvénients:

1) une bande trop large produit un mélange des signaux, et souvent les sursauts radiosolaires ont un spectre *étroit* (exemple: les sursauts d'orage dont la bande spectrale est de l'ordre de quelques 100 kHz);

2) une constante d'intégration trop grande adoucit démesurément les enregistrements et fait perdre les phénomènes de courte durée (exemple: certains sursauts d'orage ont une durée de l'ordre de 0.1 s).

4. — Cas du récepteur imparfait.

Un récepteur réel donne toujours un bruit de fond.

Contentons-nous d'énoncer les principales causes de ce phénomène.

a) *Bruit thermique dans les résistances*, et principalement dans la composante résistive de l'impédance d'entrée. Cette impédance doit avoir une composante résistive, sans quoi l'antenne n'aurait aucun pouvoir absorbant.

b) *Effet de granulation* (bruit Schottky), dû à la structure discontinue du faisceau électronique dans les tubes, principalement le tube d'entrée.

c) *Bruit induit de grille*: si le tube d'entrée est une triode, des tensions

aléatoires sont induites sur la grille de commande lors du passage des électrons individuels et réagissent sur les autres électrons du faisceau.

d) *Bruit de partition*, dû au partage aléatoire des électrons vers les diverses électrodes des tubes multiélectrodes (exemple: pentodes).

e) *Scintillations*, ou formation de « cratères » sur les cathodes à oxydes, dont il résulte une modification aléatoire de l'intensité du faisceau électronique. On montre que le spectre de ces fluctuations est limité aux fréquences basses et s'annule pratiquement vers 400 Hz.

f) *Retour des électrons*, rebondissant par exemple d'une manière aléatoire sur l'anode.

g) *Pertes d'électrons*, dues à une structure géométrique défectueuse du tube, etc.

Ces divers facteurs conditionnent l'intensité du bruit de fond aux hautes fréquences, et les fluctuations de gain aux basses fréquences.

5. — Le facteur de bruit.

Considérons maintenant un récepteur réel toujours imparfait (Fig. 21). Une puissance kT_0B est appliquée à l'entrée; elle est amplifiée de sorte qu'à la sortie une puissance GkT_0B est recueillie. Mais il s'y ajoute une puissance N représentant la contribution du bruit de fond du récepteur.

Par définition, le *facteur de bruit* est (*)

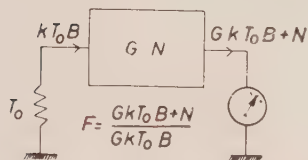


Fig. 21. — Facteur de bruit d'un récepteur.

$$F = \frac{GkT_0B + N}{GkT_0B}$$

Le facteur de bruit F donne donc une indication *globale* des performances du récepteur en ce qui concerne le bruit de fond.

$$F_{db} = 10 \log_{10} F$$

est la « figure de bruit » (noise figure);

$$T_N = \frac{N}{GkB} = (F - 1)T_0,$$

est la « température de bruit ».

(*) Ordinairement, $T_0 = 290^\circ\text{K}$; $kT_0 = 4 \cdot 10^{-21} \text{ J}$.

Cette indication n'est valable que si l'on suppose le bruit de fond distribué uniformément en fréquence. Observons encore que l'étage d'entrée est supposé connecté à une résistance adaptée.

Lorsqu'on envisage séparément les différentes composantes de fréquence

$$dN(\nu) = G(\nu) k T_N(\nu) d\nu,$$

la « température moyenne de bruit » est alors définie par

$$\bar{T}_N = \frac{\int_0^\infty G k T_N d\nu}{\int_0^\infty G k d\nu} = \frac{1}{G_m B} \int_0^\infty G T_N d\nu.$$

6. — Influence du facteur de bruit sur la précision des mesures.

La formule obtenue obtenue à la Section 3.2 se généralise immédiatement. En présence d'un facteur de bruit F , on a (Fig. 22)

$$\Delta T_a = \frac{T_a + (F-1)T_0}{\sqrt{B\tau}}.$$

Exemples: a) $T_a = 300^\circ\text{K}$, $T_0 = 290^\circ\text{K}$, $F = 10$, $B = 1\text{ MHz}$, et $\tau = 1\text{ s}$:

$$\Delta T_a = 3^\circ\text{K} \quad \text{soit} \quad 1\%.$$

Pour $F = 1$, ΔT_a serait de l'ordre de 1% .

b) mêmes conditions mais $T_a = 3^\circ\text{K}$

$$\Delta T_a = 3^\circ\text{K} \quad \text{soit} \quad 100\%.$$

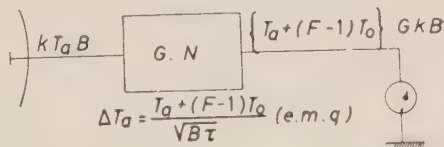


Fig. 22. — Fluctuations à la sortie d'un récepteur réel (en présence de bruit de fond).

L'influence du facteur de bruit est d'autant plus désastreuse que les températures à mesurer sont basses.

En conclusion: quand on dispose de grandes antennes (T_a élevées), on peut se contenter de récepteurs médiocres. Quand les antennes sont petites, ou quand les températures à mesurer sont basses (exemple: mesures galactiques) les récepteurs doivent être excellents. Heureusement, le flux galactique est stable de sorte que de grandes constantes d'intégration peuvent être employées. Tel n'est pas le cas en physique solaire.

7. - Mesure du facteur de bruit et calibration du récepteur.

La technique couramment utilisée consiste à connecter à l'entrée du récepteur soit une résistance adaptée chauffable, soit un générateur de bruit équivalent à une résistance chauffée et donnant un bruit distribué uniformément en fréquences. On chauffe la résistance à $T^\circ\text{K}$, ou on agit sur le générateur de bruit, de manière à doubler la puissance observée à la sortie du récepteur (Fig. 23).

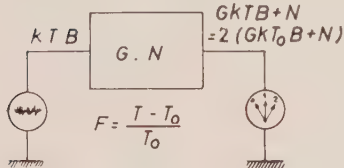


Fig. 23. - Mesure du facteur de bruit à l'aide d'une résistance chauffée ou d'un générateur équivalent.

a) *Mesure au moyen d'une résistance chauffée.* La Fig. 23 montre immédiatement que

$$F = \frac{GkT_0B + N}{GkT_0B} = \frac{T - T_0}{T_0}.$$

Cette méthode n'est pas toujours applicable. De plus, elle n'est pas souvent pratique. On remplace alors la résistance chauffable par un générateur de bruit équivalent.

b) *Mesure au moyen d'un générateur à diode saturée.* Du fait de la structure discontinue du faisceau électronique le courant anodique d'une diode présente des fluctuations. Lorsque tous les électrons émis par la cathode sont recueillis par l'anode (absence de charge d'espace, diode saturée), lorsque le filament de la diode est métallique (tungstène pur, absence de scintillations), lorsque la distribution des vitesses électroniques est maxwellienne (ce qui implique une certaine construction du tube) et lorsque le temps de transit des électrons est négligeable ainsi que les self-inductances et capacités parasites, etc., les fluctuations sont uniformément distribuées en fréquence et le carré de leur écart type est donné par la formule de Schottky:

$$\bar{i}^2 = 2e_0IB,$$

I étant l'intensité du courant anodique et e_0 la charge de l'électron.

Un générateur du type représenté par la Fig. 24 et fermé sur une résis-

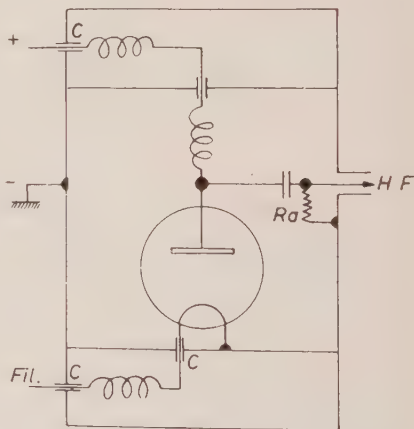


Fig. 24. - Un générateur de bruit à diode saturée. Observer les dispositifs de filtrage dans les connexions d'alimentation.

tance R donnera alors une puissance de bruit

$$P = \frac{1}{4} i^2 R = \frac{1}{2} e_0 I B R .$$

Appliquons le dispositif à l'étage d'entrée du récepteur et réglons I de manière à doubler la puissance de sortie:

$$G(kT_0 B + \frac{1}{2} e_0 I B R) + N = 2(GkT_0 B + N)$$

comme

$$N = (F - 1) G k T_0 B$$

il vient

$$F = \frac{e_0 I R}{2 k T_0} .$$

Pour $R = 50 \, \Omega$ et $T_0 = 290 \, ^\circ\text{K}$

$$F = 1\,000 I :: I_{\text{mA}} .$$

Le facteur de bruit est donc égal au nombre de milliampères anodiques d'une diode saturée, nécessaires pour doubler la puissance de sortie.

Les diodes ordinaires conviennent jusqu'aux ondes métriques. En fait, leurs performances sont limitées par le temps de transit des électrons. Aux ondes décimétriques il est bien préférable d'utiliser des diodes coaxiales (par exemple du type TT 1 Bendix).

c) *Autres générateurs de bruit.* Un tube fluorescent traversant un guide d'onde constitue un excellent générateur de bruit quand il est mis sous tension. Non excité, le tube n'exerce que peu d'influence sur la propagation. Une bonne adaptation est réalisée en inclinant le tube d'environ 15° sur l'axe du guide.

Un cristal semi-conducteur parcouru par un courant inverse dans le sens de la plus grande résistance constitue également un générateur de bruit dont le spectre est suffisamment uniforme.

De tels générateurs fonctionnent jusqu'aux ondes très courtes. Ils doivent cependant être calibrés car ils n'ont rien d'absolu. Les générateurs à cristaux ne paraissent pas fournir de mesures reproductibles dans la bande cm-mm.

d) *Calibration du récepteur.* Le but de cette calibration consiste à inscrire une échelle de température d'antenne sur l'enregistrement. Elle est généralement effectuée au moyen d'un générateur de bruit équivalent à une résistance chauffée, non au moyen d'une résistance chauffée elle-même parce que 1) l'intervalle de températures nécessaires est trop étendu, et une résis-

tance ne subsisterait pas, ou ne conserverait pas la même valeur, aux hautes températures indispensables pour calibrer le haut de l'échelle; 2) une résistance chauffée est un générateur trop lent, et la mesure prendrait trop de temps.

On utilise aux fins de calibration soit un générateur à diode saturée (1 mA de courant anodique pour une diode saturée adaptée à 50 Ω correspondant à 290 °K), soit un générateur à tube fluorescent etc.

Même à l'aide de ces générateurs il est difficile de calibrer le haut de l'échelle; une méthode consiste à amplifier le bruit à l'aide d'un amplificateur à bande plus large que celle du récepteur avant de l'appliquer à l'entrée. Une autre solution consiste à utiliser une diode coaxiale en parallèle sur l'antenne (c'est-à-dire intervenant comme un élément de ligne de transmission dans le câble d'antenne) et à travailler par addition: dans ce cas, la première partie de l'échelle est calibrée directement, l'antenne étant tournée vers un point froid du ciel; les parties successives s'étalonnent en tournant l'antenne vers des sources de plus en plus chaudes.

8. - L'étage d'entrée.

Le théorème des réseaux en cascade (Fig. 25) montre que, si le premier étage d'un récepteur a un gain suffisant, son bruit de fond détermine celui du récepteur entier. En effet le facteur de bruit d'une cascade de deux réseaux

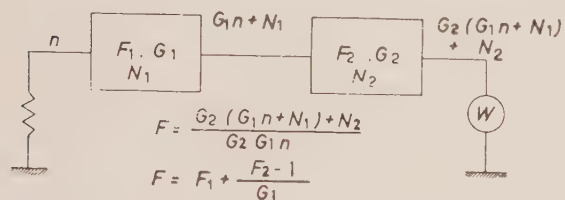


Fig. 25. - Le théorème des réseaux en cascade.
Facteur de bruit résultant.

dont le premier a un facteur de bruit F_1 et un gain G_1 tandis que le second a un facteur de bruit F_2 et un gain G_2 est donné par

$$F = F_1 + \frac{F_2 - 1}{G_1}.$$

Si G_1 est élevé, $F = F_1$ quel que soit F_2 . La presque

totalité du bruit de fond du récepteur est donc engendrée dans l'étage d'entrée.

Actuellement, l'obtention d'un faible facteur de bruit est rendue possible a) par l'existence de tubes électroniques haute fréquence ayant un gain suffisant et un bruit faible, b) par les techniques nouvelles du MASER (Microwave amplification by stimulated emission of radiation) et des amplificateurs paramétriques ou MAVAR (amplification by variation of reactance).

a) *Amplification par tubes électroniques.* L'amplification est possible s'il existe à la fréquence considérée, un tube dont le facteur de mérite

$$f = \frac{g_m}{2\pi(C_e + C_s)},$$

est suffisant (g_m = transconductance, C_e et C_s = capacité d'entrée et de sortie). D'autre part, la fréquence de travail du tube est limitée par le temps de transit des électrons, qui a le même effet qu'une résistance d'amortissement

$$R_a = \frac{1}{g_m L_k C_{gk} \omega^2},$$

placé en parallèle sur le circuit résonnant d'entrée. La largeur de bande de ce circuit résonnant est $B = 1/2\pi RC$, où C s'identifie à C_{gk} (capacité grille-cathode) et où R contient R_a . Un haut facteur de mérite s'obtient en *accroissant* la transconductance (fortes densités électroniques ce qui implique des cathodes spéciales, réduction de l'espace grille-cathode à quelques dizaines de microns, construction spéciale de la grille en fils fins très serrés) et en *réduisant* les capacités parasites (réduction des effets électrostatiques par une disposition judicieuse des électrodes, précautions de montage). Observons que la self-inductance parasite L_k des connexions internes de cathode est toujours en série avec la self-inductance du circuit résonnant d'entrée, placée entre les bornes d'accès de la grille et de la cathode. Pour ω élevé, R_a est petite et le circuit d'entrée très amorti ce qui réduit la hauteur de la courbe de résonance; l'amplification devient négligeable. En résumé, les tubes spéciaux pour haute fréquence ont toujours de faibles capacités interélectrodes, de grandes transconductances, et de faibles self-inductances parasites.

La structure granulaire du faisceau électronique, le partage aléatoire des électrons, les pertes et rebondissements d'électrons, etc., entraînent toujours un bruit de fond se manifestant comme une fluctuation du courant anodique. Un tube parfait de mêmes caractéristiques présenterait les mêmes fluctuations anodiques si l'on connectait à sa grille une résistance R_{eq} portée à $T_n = 290^\circ \text{K}$. Cette résistance équivalente de bruit n'intervient pas dans l'amortissement. Le facteur de bruit du tube est

$$F = 1 + \frac{R_{eq}}{R_a}.$$

Pour une triode $R_{eq} = 2.5/g_m$. Pour une pentode, elle est beaucoup plus élevée: $R_{eq} = (I_a/(I_a + I_e))((2.5/g_m) + (20 I_e/g_m))$, I_a et I_e désignant les courants anodiques et d'écran. Le Tableau II donne quelques exemples.

TABLEAU II.

6AK5 triode	$g_m = 6\,670 \mu\text{mho}$	$R_{eq} = 385$
6 J 4 triode	12 000	210
6 J 6	5 300	470
6AG5 triode	5 000	1 640
6AK5 pentode	5 000	1 880
PTT 214 P triode	13 500	100 env.
EC 56 triode	13 500	—

Le meilleur tube aux ondes métriques paraît être la PTT 214 P française monté en triode. Aux ondes décimétriques la meilleure triode paraît être la EC 56 (tube à disques scellés) ou la EC 157.

WALLMAN [15] a montré qu'en montant deux triodes de la manière indiquée par la Fig. 26, on peut obtenir le gain élevé d'une pentode sans rencontrer les

inconvenients du bruit de fond. Un tel montage *cascode* est devenu d'un usage courant dans les applications radioastronomiques. Il est souvent avantageux de neutraliser la capacité grille-anode du premier tube par un circuit résonnant, ce qui augmente en fait le facteur de mérite. La prise médiane sur la self d'entrée, placée à la première grille, doit être choisie judicieusement. On obtient en principe le meilleur facteur de bruit en faisant apparaître entre cette prise médiane et la cathode (extrémités de la ligne de transmission), l'impédance

$$R = (R_{eq}/R_a)^{\frac{1}{2}},$$

laquelle doit être égale à l'impédance caractéristique de la ligne de transmission et à l'impédance d'antenne (adaptation d'impédances, absence d'ondes stationnaires, rendement énergétique optimum car l'impédance de source est égale à l'impédance de charge).

Il est parfois avantageux de placer deux cascodes successifs en cascade. A titre d'exemple, deux cascodes successifs PTT 214P - 6J4 ont permis d'atteindre sur 169 MHz un facteur de bruit $F = 2.2$.

b) *Amplificateur moléculaires ou masers.* Un maser est un amplificateur contenant en principe une collection de systèmes quantifiés triplement résonnants. Au moyen d'une source auxiliaire (oscillateur de pompage), on dérange artificiellement l'équilibre thermodynamique de manière à accroître l'abondance des systèmes sur un niveau supérieur d'énergie. Au moyen de la radiation à amplifier, on provoque une chute des systèmes sur un niveau inférieur. Il en résulte une émission induite qui s'ajoute au signal, conduisant ainsi à une amplification.

Pour que le dispositif soit utilisable aux fréquences radioélectriques, il faut

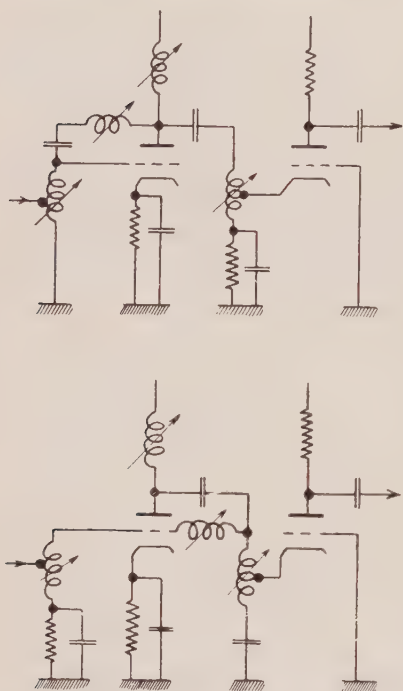


Fig. 26. Diverses versions du circuit cascode.

que le diagramme des états d'énergie contienne des niveaux très serrés. On peut s'adresser dans ce but à des systèmes atomiques (transitions hyperfines ou de structure fine), moléculaires (dédoublment des niveaux par couplage de spin ou inversion), cristallins (dédoublment magnétique), ferromagnétiques (modes magnétostatiques des ferrites), etc. Des masers à faisceaux atomiques ou moléculaires ont permis de réaliser des oscillateurs très stables (exemple, les horloges à l'ammoniac ou au césium). Les masers à l'état solide paraissent les plus prometteurs en radioastronomie.

Décrivons brièvement le principe d'un maser utilisant l'état cristallin. Un cristal de rubis ($\text{Al}_2\text{O}_3 \cdot x\text{Cr}_2\text{O}_3$) est placé dans une cavité doublement résonnante. En présence d'un champ magnétique, les niveaux d'énergie du cristal paramagnétique sont séparés. La cavité est refroidie à la température de l'hélium bouillant (1.4°K). Donnant au champ magnétique une valeur et une orientation convenable par rapport à l'axe du cristal, on crée des niveaux utilisables sur microondes (exemple, $H = 3\,900$ Oe, angle de 58° entre H et l'axe électrique, $\nu_{24} = 23\,100$ MHz, $\nu_{23} = 9\,400$ MHz; Fig. 27). En présence de radiation ν_{24} , les populations des niveaux 2 et 4 peuvent être rendues égales. L'application de la formule de Boltzmann à $T = 1.3^\circ\text{K}$ donne $N_2 - N_3 = (N/3)(h/kT) \cdot \frac{1}{2}(\nu_{23} - \nu_{34})$ où $N = N_2 + N_3 + N_4$. Si $\nu_{34} > \nu_{23}$ la différence devient négative, c'est-à-dire qu'il y a plus de systèmes sur le niveau 3 que sur le niveau 2. Il y a alors possibilité d'émission induite et par suite d'amplification sur la fréquence ν_{23} .

Les résultats obtenus par ALSOP, GIORDMAINE, MAYER et TOWNES (Columbia University et U.S. Naval Research Laboratory) [16] indiquent un produit gain-bande de 50 MHz à 9 400 MHz avec une température de bruit de 0.03°K à condition d'utiliser un amplificateur moyenne fréquence ayant une bande passante de 3.5 MHz et une constante de temps de 5 secondes après détection. A $T = 1.4^\circ\text{K}$, la limite théorique de la température de bruit est de l'ordre de $h\nu_{23}/k$, c'est-à-dire 0.4°K , limite imposée seulement par l'émission spontanée, et ceci sans intégration.

Les amplificateurs à ferrite sont rangés dans la classe des masers mais ils se rapprochent des masers. Une ferrite est un cristal ferromagnétique dans lequel, en présence d'une aimantation, les spins tendent à s'aligner en précessionnant sur le champ magnétique. Les précessions s'amortissent graduellement par collisions et il en résulte un alignement graduel des spins. Si maintenant

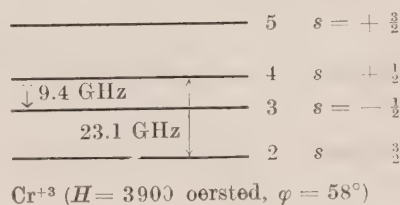


Fig. 27. — Diagramme des niveaux spectraux dans un cristal de rubis en présence d'un champ magnétique. La fréquence de pompage est 23.1 GHz. La fréquence de signal est 9.4 GHz. L'émission induite est utilisée aux fins d'amplification dans ce type de maser à l'état solide.

un faible champ magnétique créé par une onde incidente s'ajoute au champ magnétisant, les précessions recommencent. Si le champ incident oscille à la fréquence de précession, il y a résonance et de l'énergie est absorbée par la ferrite. Pour un champ magnétisant déterminé, le diagramme d'absorption présente un pic à la fréquence de résonance. On observe en fait un ensemble de pics distribués sur un intervalle à peu près continu, chacun d'eux correspondant à une configuration particulière du champ électromagnétique dans la ferrite. Le système de ces modes « magnétostatiques » dépend de la forme de l'échantillon et de l'intensité du champ magnétisant. En conséquence, une ferrite magnétisée constitue un système quantifié à résonances multiples analogue à un atome ou une molécule. On pourra utiliser cette propriété pour faire fonctionner la ferrite de la même façon qu'un maser. Trois espèces d'opérations sont possibles (magnétostatique, semistatique, électromagnétique [17]) mais l'opération magnétostatique semble la plus appropriée parce qu'elle exige le moins de puissance de l'oscillateur de pompe.

Pour une discussion générale des masers, cf. [18], [19].

c) *Amplificateurs paramétriques ou mavar.* Le principe d'un mavar consiste à introduire dans un réseau électrique une réactance non linéaire, conduite par le signal en présence d'une source auxiliaire fournissant de la puissance sur une autre fréquence. Dans ce cas, la réactance pourra emprunter de

l'énergie à la source et la restituer à la fréquence du signal en produisant une amplification.

Le schéma général du dispositif est donné Fig. 28. Trois circuits résonnants aux fréquences ν_p , ν_s et $\nu_p + \nu_s$ ou $\nu_p - \nu_s$ sont couplés par une réactance non linéaire (self ou capacité) ce qui produit les bandes latérales $\nu_l = \nu_p - \nu_s$ et $\nu_h = \nu_p + \nu_s$. MANLEY et ROWE [20] ont montré qu'alors les relations énergétiques suivantes sont satisfaites

$$P_p/\nu_p = -P_i/\nu_h - P_l/\nu_l,$$

$$P_s/\nu_s = -P_i/\nu_h + P_l/\nu_l,$$

où P désignent des puissances. Une puissance positive est une puissance cédée par la réactance; les indices se rapportant aux fréquences ν (SUHL [21], WEBER [17]).

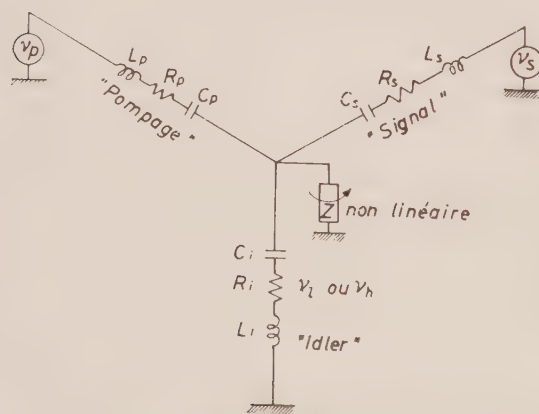


Fig. 28. - (Circuits schématisés d'un amplificateur paramétrique ou Mavar. La réactance non linéaire couple les circuits de signal (RLC_s), de pompe (RLC_p) et le circuit « idler » de dissipation (RLC_l ou RLC_h).

Le circuit de pompage travaille sur ν_p ; le circuit du signal travaille sur $\nu_s < \nu_p$; enfin le troisième circuit, ou « idler » travaille sur une bande latérale ν_h ou ν_l . On n'utilise qu'une seule bande latérale de sorte que $P_l = 0$ ou bien $P_h = 0$.

En supposant $P_l = 0$, on crée une fonction amplificatrice et modulatrice. En effet $P_h = -(\nu_l/\nu_s)P_s$. La puissance absorbée P_s est transformée en une puissance cédée P_h avec un gain de puissance ν_h/ν_s à la fréquence ν_h .

En supposant $P_h = 0$, on crée une fonction amplificatrice car $P_s = (\nu_s/\nu_l)P_l$. Le gain est ν_l/ν_s . Le produit gain-bande est constant. L'amplification est limitée seulement par la configuration du système.

Il existe actuellement trois types de mavars (ferromagnétiques, à faisceau électronique, à capacitance variable). TAKAHASHI a fait remarquer l'analogie entre masers et mavars; voir également [18].

Les mavars à capacitance variable sont les plus simples. Une diode à jonction p-n présente une capacité variant non linéairement avec la tension quand elle est polarisée dans le sens de la plus grande résistance (*). Quand par exemple on courtcircuite une cavité triplement résonnante à 3 500 MHz, 3 200 MHz et 1 200 MHz par une telle diode à jonction on constitue un amplificateur paramétrique susceptible de fournir un gain de 19 décibels à 1 200 ou 2 300 MHz, sur une bande de 1 MHz, avec un facteur de bruit de 4.8 db et une puissance de pompage de 100 mW sur 3 500 MHz. De tels résultats ne sont pas aussi spectaculaires que ceux du maser mais ils sont encourageants. L'avantage du mavar à capacitance variable sur le maser est qu'il n'exige ni champ magnétique ni refroidissement, et qu'il peut fonctionner à des fréquences basses (exemples, 400 MHz, 10 MHz etc.). Sur 20 MHz un mavar équilibré, construit par Airborne Instruments, et utilisant des diodes IN 470 a fourni un gain de 10 db sur une bande passante de 2 MHz avec une température de bruit de 40 °K ce qui signifie une figure de bruit de 0.5 db.

9. — Les étages suivants.

Nous n'insisterons pas sur ces dispositifs dont la technique est devenue classique.

a) *Oscillateur local, mélangeur.* Bornons-nous à dire que tout bon tube amplificateur à la fréquence de travail peut constituer un bon oscillateur local.

(*) Cette capacité est due à la double couche et à l'étendue de la zone de déplétion au voisinage de la jonction; elle varie non linéairement suite au processus non linéaire de formation d'une charge d'espace. Par exemple, une jonction p-n de germanium donne une capacitance variable dans le rapport de 3 à 1 pour une polarisation variant de 15 V.

Les qualités demandées sont *a*) une excellente stabilité de fréquence (parfois, pilotage par quartz); *b*) une excellente stabilité d'amplitude (ce qui implique une bonne stabilité des tensions d'alimentation). Le bruit de l'oscillateur local est confiné à une bande étroite. Quand il est excessif (par exemple dans les klystrons), il est possible d'utiliser des mélangeurs équilibrés. Le choix d'une fréquence *supérieure* à la fréquence centrale est avantageux car l'écart à la fréquence image est alors maximum. Les mélangeurs *triode* sont surtout utilisés. Il convient que l'oscillation locale bloque le tube pendant une partie du cycle (amplitude en volts égale à 0.7 fois le potentiel de « cut-off »). On peut évaluer dans les conditions optima à $0.28 g_0$ la transconductance de conversion d'une triode et à $13/g_0$ sa résistance équivalente de bruit, g_0 désignant la transconductance du tube au voisinage du potentiel de grille nul.

Aux longueurs d'ondes décimétriques des mélangeurs à cristaux semi-conducteurs (silicium) sont le plus souvent utilisés. Aux ondes centimétriques et millimétriques, cette technique devient la seule applicable. Aux très hautes fréquences, l'amplification du signal d'antenne peut devenir impossible et ces mélangeurs sont alors placés directement sur la ligne d'antenne; il est évident que dans ce cas le choix du cristal est déterminant pour le facteur de bruit. On utilise également des mélangeurs à cristaux équilibrés dans lequel le signal d'antenne arrive en phase à deux cristaux les plus rigoureusement semblables possibles tandis que le signal de l'oscillateur local y arrive en opposition de phase; on recueille la fréquence intermédiaire différentiellement à partir des deux cristaux; il en résulte alors que le bruit de l'oscillateur local est, sinon éliminé, du moins fortement réduit. Pour une description de ces dispositifs voir [22].

b) Amplificateur de fréquence intermédiaire. Généralement, ces amplificateurs sont constitués par un certain nombre de multiplets de pentodes (multiplets décalés). En accordant convenablement les étages d'un multiplet amplificateur et en leur donnant une largeur de bande appropriée, il est possible de réaliser une bande large à sommet plat et de forme quasi rectangulaire ce qui présente certains avantages. Il convient d'apporter beaucoup d'attention à la forme de la bande passante parce que son inspection permet en général de déceler les traces de régénération, ou retour du signal amplifié au premier étage, qui sont désastreuses pour le bruit de fond même si elles ne sont accompagnées d'aucune oscillation proprement dite du système. Ces régénérations sont très visibles sur le bande, où elles se traduisent par divers accidents (creux, sommets aigus, etc.); pour les éviter, il est intéressant de monter l'amplificateur sur un châssis long et étroit, fonctionnant comme un guide d'onde au dessous de la fréquence de coupure ce qui atténue considérablement le signal de retour. Enfin le nombre de multiplets à utiliser dépend principalement de l'amplification et de la largeur de bande à obtenir: le réglage n'est d'ailleurs pas critique. Donnons un exemple relatif à un récepteur travaillant sur

600 MHz. On n'a pas utilisé d'amplification à la radiofréquence de sorte que le mélangeur a été connecté directement à l'antenne:

a) 1 cascode 30 MHz + 1 quadruplet de pentodes 6AG5 (préamplificateur). Gain en puissance 60 db; largeur de bande 7 MHz.

b) 1 triplet de 6AG5 + 1 triplet formé de deux 6AG5 et d'une 6AN5, cette dernière étant suivie d'une diode détectrice 6AL5 (amplificateur moyenne fréquence proprement dit). Gain en puissance 75 db; largeur de bande 6 MHz.

Nous utilisons régulièrement le principe de la contre-réaction totale en continu. Les tubes sont alimentés à partir d'une tension très basse (90 V) en plaçant une grande résistance (10 000 Ω) dans le circuit de cathode. La cathode est découplée à la masse en haute fréquence par une capacité de l'ordre de 1 000 pF. Dans ces conditions, le tube recherche lui-même, en continu, son point de fonctionnement et le gain est stabilisé. La stabilité du gain est excellente pourvu que les résistances de cathode et la basse tension soient constantes.

c) *Stabilité de gain; tension d'alimentation.* L'une des causes des fluctuations du récepteur radioastronomique est la variation aléatoire du gain, résultant: a) de l'effet de scintillation; b) des variations aléatoires des tensions d'alimentation. Les fluctuations résultant des variations du gain sont fortement réduites par le principe de la rétroaction totale en continu décrit ci dessus.

Les systèmes électroniques classiques permettent d'obtenir des tensions continues d'alimentation (dans nos applications, + 150 V et - 90 V) stables dans le temps à 1/40 000 près. Cette stabilité est tout à fait suffisante pour le but poursuivi. De même, la stabilisation électronique des courants de chauffage des filaments peut être effectuée à 1/3 000 près. Quelques uns de ces systèmes ont été transistorisés; leur stabilité, surtout vis-à-vis des variations brusques de la tension du réseau, nous a paru meilleur que celle des systèmes à diode saturée commandant une boucle de rétroaction, que nous avons utilisés jusqu'à présent. Moyennant de telles précautions les variations du gain d'un récepteur radioastronomique ayant un gain de puissance de l'ordre de 100 db peuvent ne pas dépasser 5% dans un espace de six mois, et 1% sur l'espace d'une journée. D'autre part, l'absence de dérives du zéro est une question de stabilité d'impédance d'antenne et de stabilité des tensions d'alimentation: ces dérives peuvent être amenées également à des valeurs négligeables.

10. — Types de radiotélescopes.

Nous avons mentionné précédemment combien il est difficile, dans une classification, de séparer l'antenne et le récepteur. Une classification intéressante a été donnée récemment par E. J. BLUM [23]. Nous distinguerons ici plusieurs types de radiotélescopes.

a) *Systèmes à comparaison occasionnelle.* La comparaison s'effectue en remplaçant occasionnellement l'antenne par une source étalon de bruit. Cette source fournit, à la sortie du récepteur, la même puissance P_s que si l'antenne était tournée vers la source à mesurer. Dans le cas de la mesure directe, P_s est donné par

$$P_s = k \left\{ \frac{1}{4\pi} \int_{\nu, \Omega} T_b G_a G_r d\nu d\Omega + \int_{\nu} [T_b(1 - \eta) + T_R(F - 1)] G_r d\nu \right\},$$

où T_b est la température de brillance de la source, G_a et G_r le gain d'antenne et du récepteur à la fréquence ν , T_0 la température physique de l'airien (antenne et ligne), η le facteur d'efficacité et T_R la température de référence (ordinairement 290 °K) adoptée pour la mesure du facteur de bruit F .

Les quantités variables ou fluctuantes intervenant dans cette expression sont G_a (variables par effet de sol), η (idem), T_0 (la température physique du câble peut varier), G_r (fluctuation de gain du récepteur), et F (variations du facteur de bruit par variation de gain).

G_a et η sont stabilisés par une construction et un emplacement convenable de l'antenne. G_r ainsi que F sont stabilisés par l'emploi de la rétroaction totale en continu et la stabilisation des tensions et courants d'alimentation. Le niveau moyen du bruit de fond est compensé par une contre-tension appliquée à la sortie. Néanmoins, on s'est attaché à faire disparaître ce niveau de bruit par l'adoption d'autres dispositifs décrits ci-après. Notons qu'aucun de ces dispositifs n'élimine la fluctuation statistique du bruit.

b) *Systèmes à comparaison fréquente ou périodique.* Dans le système de Dicke, on module le signal d'antenne à une fréquence relativement basse tandis que la sortie du récepteur est connectée à un amplificateur accordé sur cette fréquence et à bande étroite. Dans ce cas, la seule contribution du bruit est celle présente sur l'étroite bande de fréquence à la sortie. De plus, on a conféré au signal d'antenne une individualité qui permet de le reconnaître dans le bruit.

Dans le système de Ryle, une permutation est faite à l'entrée du récepteur entre l'antenne et une source étalon de bruit (diode saturée); les réponses à la sortie sont envoyées séparément et en synchronisme à deux circuits intégrateurs et la différence des réponses intégrées est effectuée. La source de bruit est conduite automatiquement, par un servomécanisme, de manière à annuler cette différence. Le récepteur intervient ainsi comme un appareil de zéro. Le résultat de la mesure est lu sur le générateur de bruit.

c) *Systèmes à double modulation.* En introduisant une permutation double de l'antenne et de deux sources connues de bruit, et en effectuant une double détection synchrone, il est possible d'inscrire sur l'enregistrement une échelle

de calibration. Si les deux sources sont des résistances chauffées, la calibration devient absolue.

d) *Système à comparaison continue.* Une même antenne est connectée simultanément à deux récepteurs. Les réponses à la sortie sont envoyées à un *multiplicateur* et la valeur moyenne du produit est effectuée. Si les réponses en tension V sont $G_1 s + N_1$ et $G_2 s + N_2$ (G_1, G_2 = gains; N_1, N_2 = tensions de bruit), on a

$$\overline{(G_1 s + N_1)(G_2 s + N_2)} = G_1 G_2 \overline{s^2},$$

parce que la tension de signal s et les tensions de bruit N_1, N_2 ne sont pas corrélées.

Observons que la disparition du bruit n'est pas totale. En effet, suite aux propriétés du circuit d'antenne, une partie du bruit thermique de l'impédance d'entrée du récepteur 1 est envoyée au récepteur 2. Il en résulte que N_1 et N_2 ne sont pas complètement indépendantes.

e) *Systèmes à corrélation instantanée.* Un interféromètre est constitué de deux antennes. Leurs réponses individuelles sont amplifiées puis multipliées (ou l'inverse). Si s_1 et s_2 sont les signaux d'antenne, on a

$$\overline{(G_1 s_1 + N_1)(G_2 s_2 + N_2)} = G_1 G_2 \overline{s_1 s_2}.$$

Ici encore, il y a réduction du bruit de fond.

f) *Systèmes à corrélation non instantanée.* Dans l'une des branches d'un interféromètre, on ajoute puis on soustrait périodiquement une longueur supplémentaire de câble égale à $\lambda/4$. Une détection synchrone est faite ensuite à la sortie du récepteur. En principe, les deux signaux de sortie sont $G(s_1 + s_2) + N$ et $G(s_1 - s_2) + N$. Ces signaux sont détectés quadratiquement avant détection synchrone. La différence est faite après intégration; on a

$$\overline{(G(s_1 + s_2) + N)^2} - \overline{(G(s_1 - s_2) + N)^2} = 4G^2 \overline{s_1 s_2},$$

puisque N n'est pas corrélé avec s_1, s_2 . Le bruit de fond a disparu. L'opération est équivalente à la formation d'un produit.

g) *Récepteurs spectrographiques.* Les récepteurs panoramiques utilisés en radioastronomie solaire sont décrits dans le même ouvrage par J. P. WILD [24]

DEUXIÈME PARTIE

LA RADIATION SOLAIRE EN RADIOASTRONOMIE

Nous avons rappelé dans l'Introduction que, contrairement à ce qui a lieu dans le domaine optique, le spectre radioélectrique solaire ne présente aucune raie observée jusqu'à présent (*). Ce spectre se limite à un fond continu, et si son interprétation ne peut avoir la même richesse que celle du spectre optique où les raies sont nombreuses, elle est pourtant fondamentale parce que *a)* elle nous permet d'étudier directement les couches atmosphériques élevées, optiquement minces aux fréquences lumineuses; *b)* le fond continu comporte une composante permanente assez stable, mais également diverses composantes transitoires qui peuvent être beaucoup plus intenses que la première. L'étude radioélectrique du Soleil doit donc se diviser en deux sections:

a) L'étude du soleil calme. On dit que le Soleil est calme (radioélectriquement) quand seule la composante permanente est émise. Cette définition est subjective étant donné que le Soleil peut être calme à une fréquence déterminée et variable à d'autres. Cependant on peut isoler une *composante de base* qui est la radiation naturelle de l'atmosphère solaire en l'absence de toute espèce d'activité. Il s'agit d'une radiation émise à l'équilibre thermodynamique local, par les électrons libres du milieu ionisé animés de vitesses thermiques lorsque leurs trajectoires sont déviées par les ions. Au prix de quelques modifications, il est possible d'appliquer à cette composante de base les mêmes méthodes que celles utilisées en astrophysique optique dans l'étude de l'atmosphère solaire. On obtient ainsi des informations sur la densité électronique et la température électronique à des altitudes qui peuvent être très supérieures à celles atteintes par les méthodes optiques. Malheureusement, le problème s'est compliqué à mesure que nous le connaissons mieux et il apparaît que la solution n'est pas unique surtout si l'on tient compte de phénomènes comme les champs magnétiques ou les irrégularités de densité électronique. De plus, l'imprécision des distributions de brillance, et surtout le fait que l'on ne dispose que d'un fond continu, limitent encore la valeur des résultats.

(*) Il existe néanmoins quelques possibilités théoriques d'observation de raies faibles en absorption [25]. Pour 2.303 cm (transition $2^2S_{\frac{1}{2}} - 2^2P_{\frac{3}{2}}$ de H) $\Delta T = 1^\circ \text{K}$ si $dT/dh > 100^\circ \text{K/km}$, c'est-à-dire dans les régions à fort gradient thermique (protubérances, éruptions). Les autres longueurs d'onde sont moins probables (10.2 cm ; 27.7 cm Paschen, etc.). Les raies correspondantes de He^+ sont situées dans des régions spectrales inadéquates ($2S_{\frac{1}{2}} - 2P_{\frac{1}{2}}$: $14\,020 \text{ MHz}$; $2P_{\frac{3}{2}} - 2S_{\frac{1}{2}}$: $161\,510 \text{ MHz}$).

b) *L'étude du Soleil actif.* On dit que le Soleil est radioélectriquement actif quand sa radiation comporte des transitoires. Ici cette étude est très riche. Les transitoires sont en effet très variés. Leur abondance et leur distribution sont fonctions de la fréquence. Il y a des transitoires à profil raide (*sursauts*) d'intensité et de durée variables, et des transitoires à profil adouci (variations lentes). Aux ondes décimétriques, certaines absorptions peuvent être aussi constatées. D'une manière générale, les enregistrements sur ondes longues comprennent surtout des transitoires raides tandis que les enregistrements sur ondes courtes comportent plutôt des transitoires adoucis. Un transitoire peut être raide sur ondes longues et adouci sur ondes courtes. Tout transitoire présente un spectre dynamique (intensité en fonction de la fréquence et du temps) qui le caractérise. Il s'agit rarement de phénomènes thermiques car les températures de brillance rencontrées s'établissent trop brusquement et sont beaucoup trop élevées. Il y a lieu d'envisager au contraire des émissions résultant de mouvements électroniques coordonnés, au lieu de mouvements dispersés. Les investigations sur la nature et l'origine des transitoires ont mis en évidence deux grandes classes de processus conduisant à une émission possible (ondes de plasma ou hydromagnétiques, radiation de synchrotron) mais il y en a peut être d'autres et la question reste largement ouverte. En tout cas, les transitoires de la radiation solaire ont permis de découvrir des phénomènes qu'il n'aurait jamais été possible de mettre en évidence autrement. Certains transitoires ont un correspondant optique, d'autres ne sont associés à aucun événement optique connu. Certains types sont associés à des radiations corpusculaires (particules aurorales ou rayons cosmiques). Dans une large mesure l'étude des transitoires permet de préciser la liaison entre phénomènes d'activité solaire et de mieux définir leurs éventuels effets géophysiques.

I. - Le soleil calme.

1. - Définition de la composante de base.

L'intensité de la radiation permanente du Soleil peut être définie comme l'enveloppe inférieure des enregistrements à fréquence fixe en fonction du temps, après exclusion des sursauts visibles et des rares absorptions éventuelles à condition d'opérer sur un intervalle de temps suffisant. Comme il apparaît, surtout sur ondes décimétriques, une certaine récurrence de 27 jours entre les valeurs successives du flux radioélectrique solaire, il est commode de choisir comme intervalle d'échantillonnage la durée d'une rotation solaire.

Cette définition implique que la radiation permanente, à grande échelle, est essentiellement variable. En fait, on constate que le minimum moyen d'intensité à une fréquence déterminée dépend des caractéristique optiques de la rotation envisagée. En l'absence d'un indice d'activité satisfaisant, on a pris jusqu'à présent le nombre de taches ou l'aire tachée moyenne A_n de la rotation portant le numéro n . On peut chercher à mettre T_n , la température

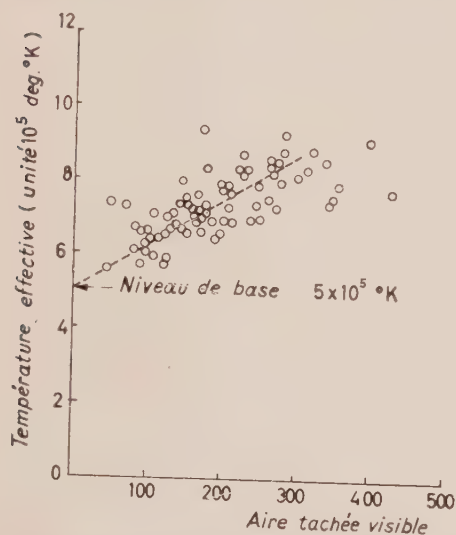


Fig. 29. - Relation entre la température équivalente du disque pour le Soleil calme et l'aire tachée visible.

équivalente minimum moyenne du disque pendant la rotation n , en corrélation avec A_n . On obtient alors un diagramme analogue à la Fig. 29. Les particularités suivantes peuvent y être remarquées: *a*) régression linéaire assez nette entre T_n et A_n ; *b*) dispersion assez forte des points d'observation. La dispersion provient du fait que l'on n'a considéré que les taches solaires, alors que bien d'autres phénomènes pourraient intervenir dans l'émission; les taches ne sont ici considérées que comme un simple indice d'activité solaire. La régression linéaire peut être extrapolée à une aire tachée nulle. On obtient alors une indication statistique sur l'intensité de la *composante de base* de la radiation solaire.

Cette composante est assez mal définie. Aux ondes les plus courtes où le Soleil est presque toujours calme, la récurrence de 27 jours reste vague parce que la *composante à variation lente* superposée à la composante de base dépend des centres d'activité qui varient pendant la rotation; de plus, l'activité radio-électrique n'est pas nécessairement liée à une activité optique. Aux ondes les plus longues, le Soleil est presque toujours actif; il est difficile d'exclure tous les sursauts; la composante à variation lente est presque toujours associée à un *orage radioélectrique* dans lequel elle est noyée. Enfin, les sources d'émission ne coïncident pas avec les taches où les phénomènes à bas niveau; elles sont situées beaucoup plus haut dans la couronne. Les effets de directivité devraient sans doute également être pris en considération. Tout cela entraîne une incertitude sur T_n .

De plus, A_n n'est pas un bon critère. En effet, si l'on recherche la corrélation entre T_n et A_{n-m} , prise m rotations solaires auparavant, il apparaît une dispersion plus faible pour $n=2$ (résultat variant suivant la fréquence). Si l'on recherche les valeurs à donner aux coefficients k_n de l'expression linéaire

$k_0 A + k_1 A_{n-1} + k_2 A_{n-2} + \dots$ de manière à maximiser la corrélation avec T_n , ces valeurs indiquent une influence décroissante des rotations $n, n-1, n-2$, etc. Cela indique que non seulement les taches présentes, mais encore les taches en voie de disparition et les taches déjà disparues, exercent une influence sur la température équivalente minimum du disque.

Il est possible d'adopter d'autres critères d'activité, par exemple l'indice des plages faculaires. Cependant, rappelons qu'aucun critère satisfaisant, tenant compte de tous les phénomènes déjà observés, n'existe à l'heure actuelle.

•

2. — Distribution spectrale de la composante de base.

Même en extrapolant à une aire tachée nulle on constate que l'intensité de la composante de base est fonction du moment choisi dans le cycle undécennal. En particulier, aux ondes métriques, les valeurs au maximum solaire sont de 10 à 20 % supérieures à celles du minimum. La variation undécennale s'atténue aux ondes courtes et disparaît aux ondes centimétriques.

L'intensité sur ondes métriques paraît devenir minimum un an avant le minimum des taches. Ce fait est en bon accord avec les mesures optiques de la température coronale. Néanmoins, suivant WALDMEIER [26], la température de la couronne polaire est minimum un an avant, et celle de la couronne équatoriale un an après le minimum des taches. La distribution électronique varie également au cours du cycle undécennal; d'après VAN DE HULST [27]

$$N_{e(\max)} = 1.8 N_{e(\min)} \quad (\text{optique}),$$

N_e désignant le nombre d'électrons libres par unité de volume. Si l'on envisage une émission thermique électronique, on a aux ondes métriques [28]

$$N_{e(\max)} = 1.5 N_{e(\min)} \quad (\text{radio}).$$

L'accord est donc satisfaisant.

Les Fig. 30 (a et b) représentent la température équivalente du disque et la densité de flux global ($\text{W} \cdot \text{m}^{-2} \cdot \text{Hz}^{-1}$) en fonction de la longueur d'onde. On observe une montée régulière de la courbe des températures équivalentes à partir des ondes centimétriques jusqu'aux ondes métriques. Observer également la chute de la courbe vers les ondes décimétriques.

Le spectre donne déjà certaines indications sur l'origine thermique de la composante. En effet, les températures rencontrées sont en bon accord avec les températures déduites de l'optique. Elles sont d'ordre coronal aux longueurs

d'onde supérieures au décimètre, d'ordre *chromosphérique* aux longueurs d'onde comprises ente 1 dm et 1 cm. Elles deviennent d'ordre *photosphérique* aux ondes millimétriques.

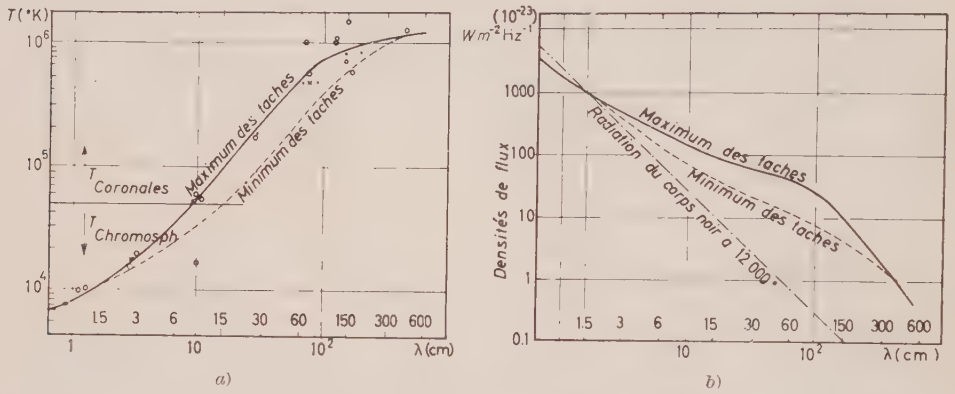


Fig. 30. Spectre de la composante de base.

La Table III [29] donne les ordres de grandeur de la température équivalente du disque et de la densité de flux S ($\text{W} \cdot \text{m}^{-2} \cdot \text{Hz}^{-1}$) en fonction de la longueur d'onde. La différence entre maximum et minimum solaire est la plus marquée entre 500 et 2000 MHz.

TABEAU III.

(cm)	(MHz)	T_{max} (°K)	T_{min} (°K)	S_{max}	S_{min}	S	Remarques
600	50	1 100 000	1 100 000	0.6	0.6	0.0	S associée à une tache (0.005 hémisphère)
300	100	1 000 000	900 000	2.1	1.9	0.0	
150	200	900 000	600 000	7.5	5.0	0.5	
60	500	380 000	230 000	30	12	19	
30	1 000	230 000	100 000	48	21	60	
15	2 000	90 000	49 000	75	41	65	
6	5 000	31 000	24 000	160	124	70	
3	10 000	7 000	15 000	350	310	70	
1.5	20 000	10 000	10 000	840	840	—	
0.6	50 000	6 400	6 400	3 400	3 400	—	

3. — Origine de la composante de base.

Les observations de brillance confirment les résultats précédents. En particulier, les observations d'éclipses solaires montrent: a) qu'aux ondes métriques le Soleil est plus étendu que le disque visible, l'éclipse commençant avant

l'éclipse optique et se terminant après elle; *b*) qu'aux longueurs d'onde plus petites (décimétriques et centimétriques) les moments du début et de la fin de l'éclipse radioélectrique se rapprochent respectivement du premier et du dernier contact optique à mesure que la longueur d'onde décroît.

De plus, s'il s'agit d'une éclipse totale optique: *a*) aux ondes métriques un flux résiduel assez intense subsiste, par exemple 20 % à 2 m; *b*) aux ondes de plus en plus courtes ce flux résiduel est d'autant moins intense; il s'annule aux ondes centimétriques et millimétriques.

En résumé, tout se passe comme si les ondes de fréquence $\nu < \nu_0$ provenaient d'altitudes solaires $h > h_0$, avec une intensité décroissant en fonction de h .

Aux ondes métriques, la totalité de la composante de base provient de la couronne; aux ondes centimétriques, la presque totalité de la radiation provient de la chromosphère. Il existe un bon accord entre les températures équivalentes rencontrées aux diverses longueurs d'onde et les températures des couches correspondantes, déduites des mesures optiques. Par conséquent, la radiation formant la composante de base doit pouvoir s'interpréter par l'hypothèse d'une origine *thermique*. Il s'agit d'une radiation émise à l'équilibre thermodynamique local par les diverses couches, celles-ci ajoutant leur contribution au flux total.

Une telle interprétation pose un problème connu depuis longtemps en astrophysique. En principe, les éléments de départ sont: *a*) la distribution de brillance observée à chaque longueur d'onde; *b*) l'équation de transfert radiatif.

La distribution de brillance observée nous fournit les conditions aux limites permettant de résoudre l'équation de transfert. Connaissant la densité de flux par stéradian à l'intérieur de l'atmosphère, il est facile de calculer la température car celle-ci est donnée par la loi de Rayleigh-Jeans.

Cependant, quelques différences avec le cas optique doivent être soulignées ici.

a) Les distributions de brillance observées aux ondes longues et moyennes n'ont pas la symétrie sphérique. Sur ondes métriques, le Soleil apparaît elliptique. Il n'y a plus une courbe unique exprimant la variation centre-limbe mais une variation du centre au bord différente suivant l'équateur et les pôles. Un modèle sphérique n'est acceptable qu'en première approximation.

b) Il faut tenir compte de l'indice de réfraction des milieux ionisés. Cet indice provient du fait que les électrons libres du milieu, mis en oscillation forcée par une onde incidente, émettent une radiation dipolaire s'ajoutant à la radiation incidente ce qui modifie la vitesse de phase. L'indice dépend de la densité électronique, elle-même variable en fonction du lieu. Comme la variation d'indice est continue, les rayons électromagnétiques deviennent des

lignes courbes. Notons également que l'indice est inférieur à l'unité, et qu'il s'annule à une certaine fréquence critique pour une densité électronique donnée.

c) L'absorption, et par suite l'émissivité à l'équilibre thermodynamique local, est produite par les accélérations électroniques et par la dissipation de l'énergie cinétique des électrons, principalement par collisions avec les autres particules et accessoirement par radiation.

d) Quand il existe un champ magnétique, les trajectoires électroniques s'enroulent autour des lignes de force et le milieu devient anisotrope. La constante diélectrique devient tensorielle au lieu d'être scalaire. L'indice de réfraction et le coefficient d'absorption sont modifiés. Il apparaît une autre fréquence critique en relation avec la fréquence gyromagnétique pour chaque direction de propagation. Le profil coronal peut être appréciablement modifié. La théorie devrait tenir compte aussi de l'émission d'une radiation partiellement polarisée.

e) Enfin, lorsqu'une radiosource galactique (par exemple la Nébuleuse du Crabe) est occultée par la couronne solaire la source apparaît élargie et son éclat est sans doute modifié. L'élargissement apparent commence à de grandes distances du limbe (par exemple 5 rayons solaires) et l'effet d'éclipse débute à des distances supérieures.

L'élargissement apparent peut s'expliquer par des irrégularités d'indice de réfraction, distribuées d'une manière aléatoire (paquets d'électrons libres) et il est donc nécessaire de tenir compte de ces fluctuations d'indice dans l'élaboration des modèles d'atmosphère solaire radioélectrique [29a].

Comme une interprétation théorique satisfaisante devra tenir compte de ces divers facteurs, nous sommes encore loin d'une solution définitive au problème de la composante de base.

4. - Equation de transfert radiatif.

À l'équilibre thermodynamique local, la fonction-source est donnée par la formule de Rayleigh-Jeans. Dans un milieu isotrope d'indice n ,

$$B_\nu(T) = \frac{2kT\nu^2}{c^2} n^2,$$

puisque la vitesse de phase des ondes électromagnétiques est $v = c/n$. En fait, $B_\nu = 2kTn^2/\lambda_0^2 = 2kT/\lambda^2$, λ désignant la longueur d'onde dans le milieu et $\lambda_0 = n\lambda$ la longueur d'onde dans le vide.

La réfraction agissant sur la direction des rayons et par suite sur les angles

solides, une simple application des lois de Descartes montre que dans un milieu d'indice variable, $n^2 d\Omega$ est conservatif. En conséquence il faut définir la densité de flux par stéradian I_ν comme suit (voir Première Partie, I Section 4):

$$dP_\nu = \frac{I_\nu}{n^2} \cdot d\nu \cdot n^2 d\Omega \cdot dA \cos \theta,$$

ce qui montre que si dans l'équation de transfert relative à un milieu non réfringent ($n=1$) figurent I_ν et B_ν , ces quantités doivent être remplacées par I_ν/n^2 et B_ν/n^2 dans l'équation de transfert relative à un milieu d'indice n . Cette équation prend alors la forme simple

$$\frac{d}{ds} \left(\frac{I_\nu}{n^2} \right) = - \frac{K'_\nu}{n^2} (I_\nu - B_\nu),$$

où K'_ν est le coefficient d'absorption et ds un élément d'arc compté suivant le rayon, dans le sens de la propagation (ds est une longueur *géométrique*).

Nous n'insistons pas sur l'intégration de cette équation différentielle élémentaire. Rappelons que, t étant compté à l'inverse de s sur le rayon à partir de l'observateur (0), on a

$$\left(\frac{I_\nu}{n^2} \right)_0 = \int_0^\infty \frac{B_\nu}{n^2} \exp [-\tau_\nu] d\tau_\nu,$$

où

$$\tau_\nu = \int_0^t K'_\nu dt,$$

désigne la profondeur optique du point de coordonnée t sur le rayon. Si n est une fonction continue du point, le rayon est une courbe et toutes les intégrales deviennent *curvilignes*. En cela réside la seule différence avec le cas optique.

Un observateur dans le vide ($n_0=1$) définit la température de brillance T_a par

$$I_{\nu 0} = \frac{2kT_a}{\lambda_0^2},$$

et l'on a simplement

$$T_a = \int_0^\infty T \exp [-\tau_\nu] d\tau_\nu,$$

puisque

$$B_p = \frac{2kTn^2}{\lambda_0^2}.$$

On peut également obtenir une expression de T_n en chaque point du rayon, comme dans le cas optique.

La détermination des rayons est indispensable. Pour l'effectuer, il suffit d'appliquer le principe classique de Fermat:

$$\delta \int_A^B n \, ds = 0,$$

et de le transformer en un principe de Lagrange par l'introduction des équations paramétriques $x = x(t)$ d'une courbe passant par A, B . L'indice n s'exprime en fonction de $x(t)$ et éventuellement de $\dot{x}(t) = dx/dt$ s'il y a biréfringence. Ici $ds = (ds/dt) dt = \dot{s}(x, \dot{x}) dt$ et ainsi

$$\delta \int_{t_A}^{t_B} L \, dt = 0,$$

avec

$$L = n(x, \dot{x}) \dot{s}(x, \dot{x}).$$

Les équations lagrangiennes

$$\frac{\partial L}{\partial x} - \frac{d}{dt} \frac{\partial L}{\partial \dot{x}} = 0,$$

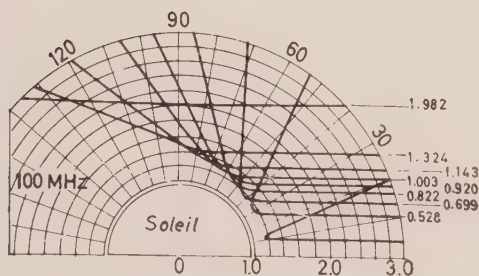


Fig. 31. - Rayons électromagnétiques dans l'atmosphère solaire sur 100 MHz (d'après JAEGER et WESTFOLD, 1950). Observer la courbure des rayons et leur enveloppe. L'indice de réfraction augmente régulièrement vers 1 du centre vers l'extérieur.

fournissent alors univoquement (à part les points singuliers) le rayon passant par A, B , ou bien le rayon passant par A et de direction donnée en A , etc.

Donnons un exemple. Dans le cas de la symétrie sphérique, l'indice $n = n(\varrho)$ est fonction de la distance ϱ au centre. On suppose que $n < 1$ tend vers l'unité lorsque ϱ croît. Les rayons sont des courbes planes définies par leur équation en coordonnées polaires (ϱ, θ) où θ est compté à partir de la direction asymptotique au rayon (celui-ci devient une ligne droite dans le vide). Comme

$$L = n(\varrho)(\dot{\varrho}^2 + \varrho^2 \dot{\theta}^2)^{\frac{1}{2}}$$

nous obtenons aisément l'équation du rayon

$$\theta = a \int \frac{d\varrho}{\varrho} (n^2 \varrho^2 - a^2)^{\frac{1}{2}},$$

a désignant la distance du centre à l'asymptote du rayon. Pour un indice de réfraction décroissant régulièrement vers l'intérieur ($n = 1$ à l'infini), les rayons sont distribués comme l'indique la Fig. 31.

5. — Réfraction et absorption.

Rappelons qu'en théorie électromagnétique classique les phénomènes de réfraction et d'absorption dans un milieu matériel sont traduits par l'existence d'un indice de réfraction complexe $u = n - icK/2\omega$, n étant l'indice de réfraction proprement dit et K le coefficient linéaire d'absorption ($\omega = 2\pi\nu$). En présence d'un tel indice complexe, une onde électromagnétique plane se propageant dans la direction r aura en effet pour expression

$$E = E_0 \exp [i\omega(t - ur/c)] = E_0 \exp [i\omega(t - nr/c)] \exp [-Kr/2]$$

et sa densité d'énergie décroîtra comme $\exp [-Kr]$.

Il est facile d'établir qu'un milieu ionisé a nécessairement un indice de réfraction complexe. En présence d'une onde incidente, les électrons du milieu oscillent en effet autour de leur position moyenne. S'il y a amortissement par collisions ou par radiation (voir II, Section 3), ces oscillations sont déphasées, et il s'ensuit que le moment dipolaire électrique par unité de volume $\mathbf{P} = -N_e e \cdot \mathbf{r}$ (N_e = densité électronique, $\mathbf{r}$ = élongation dans le mouvement oscillant) est déphasé par rapport au champ $\mathbf{E}$. En conséquence, la permittivité diélectrique ε définie par $\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} = \varepsilon \mathbf{E}$ devient une quantité complexe, ainsi que l'indice de réfraction $u = \sqrt{\varepsilon/\varepsilon_0}$. Il n'est pas nécessaire de tenir compte de la variation de la perméabilité magnétique du milieu, le moment dipolaire magnétique par unité de volume $\mathbf{M} = -\mu_0 N_e \mathbf{r} \times \mathbf{v}$ ($\mathbf{v}$ = vitesse dans le mouvement oscillant des électrons) restant négligeable par suite de la faible valeur de $\mu_0 = 1.257 \cdot 10^{-6}$ H/m.

Le mouvement oscillant des électrons autour de leur position moyenne est défini par

$$m d\mathbf{v}/dt = -e(\mathbf{E} + \mu_0 \mathbf{v} \times \mathbf{H}) - \nu_c m \mathbf{v},$$

ν_c désignant le coefficient d'amortissement par radiation et par collisions inélastiques. Aux basses fréquences, l'énergie émise sous forme de radiation

dipolaire par chaque électron individuel reste faible de sorte que l'amortissement par radiation est négligeable. L'amortissement par collisions électron-électron est également négligeable étant donné que les radiations dipolaires émises par chacun des électrons en collision se détruisent mutuellement (il ne subsiste qu'un très faible rayonnement quadrupolaire), en sorte que les orbites électroniques sont modifiées *élastiquement*. L'amortissement par collisions électron-ion est prédominant: les radiations dipolaires de l'électron et de l'ion ne se détruisent plus et il s'ensuit une modification *inélastique* de l'orbite électronique dans la collision. On constate qu'en fait le processus d'amortissement par collision met en jeu la radiation, mais d'une manière détournée.

En l'absence de champ magnétique extérieur, le second terme $\mu_0 \mathbf{v} \times \mathbf{H}$ de la force de Lorentz peut être négligé. De la solution des équations du mouvement, pour $\mathbf{E} = \mathbf{E}_0 \exp [i\omega t]$ on déduit aisément l'expression de ε :

$$\varepsilon = \varepsilon_0 \left(1 - \frac{\omega_p^2}{\omega(\omega - i\nu_c)} \right),$$

avec $\omega_p = \sqrt{N_e} e^2 / \varepsilon_0 m$ (fréquence angulaire de plasma). L'indice complexe n est donné par la formule de Maxwell

$$n = \sqrt{\frac{\varepsilon}{\varepsilon_0}} = \left(1 - \frac{\omega_p^2}{\omega(\omega - i\nu_c)} \right)^{\frac{1}{2}}.$$

Posons alors

$$\alpha = \omega_p / \omega, \quad \gamma = \nu_c / \omega$$

et développons n en série, limitée au premier ordre, par rapport à la petite quantité γ . En identifiant à l'expression $n = n - icK/2\omega$, nous obtenons ainsi

$$n = \left(1 - \frac{\omega_p^2}{\omega^2} \right)^{\frac{1}{2}}, \quad K = \frac{\omega_p^2 \nu_c}{\omega^2 n c},$$

n dépend de la fréquence et de la densité électronique N_e ; K dépend en plus du coefficient d'amortissement ν_c , identifiable comme nous l'avons vu plus haut à la *fréquence de collision électron-ion*. Nous obtiendrons plus loin une expression de ν_c .

Observons que le fait d'avoir négligé le second terme de la force de Lorentz restreint la validité des expressions obtenues aux cas où il n'existe pas de champ magnétique extérieur suffisamment intense.

6. - La fréquence critique.

Pour

$$\omega = \omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m}},$$

ou bien explicitement

$$\nu_{(\text{MHz})} = \nu_p = 9 \sqrt{N_e (m^{-3})},$$

l'indice n s'annule et le coefficient d'absorption linéaire K devient infini. En conséquence, les intégrales curvilignes figurant à la Section 3 peuvent être arrêtées au point de densité électronique critique $N_e = v^2/81$ si cette densité critique est réalisée le long du rayon. Cela a lieu, en tout cas, pour le rayon central dans une distribution à symétrie sphérique. Pour fixer les idées, on peut adopter la formule de Baumbach-Allen-van de Hulst [29]

$$N_e = 10^{14} (1.55 \varrho^{-6} + 2.99 \varrho^{-16}) \text{ m}^{-3}$$

pour la couronne, et la formule de Cillié-Menzel pour la chromosphère [30]

$$N_e = 5.7 \cdot 10^{17} \exp [-7.7 \cdot 10^{-4} (h - 500)_{\text{km}}] \text{ m}^{-3}.$$

Le Tableau IV donne, en relation avec l'altitude en fractions du rayon solaire optique, la fréquence critique en MHz et la densité électronique dans le modèle de Allen [29].

TABLEAU IV.

	Altitude en fractions du rayon du disque optique	N_e en 10^{12} m^{-3}	Fréquence critique en MHz
Chromosphère	0.0000 R_0	1 300 000	10 100
	0.0029	10 000	900
6 000 km, spicules	0.0057	2 500	450
	0.0086	25 000	1 420
	0.0101	1 000	284
	0.0144	630	225
	0.029	400	180
Couronne	0.030	350	168
	0.06	260	145
	0.10	176	119
	0.2	78	80
	0.4	25	45
	0.6	11	30
	0.8	5.7	21.5
	1.0	3.1	15.9

La Table IV indique un rebroussement à l'altitude des spicules. Il en résulterait qu'à une altitude inférieure la radiation de fréquence inférieure à 1420 MHz (simple coïncidence avec la raie de l'hydrogène) ne pourrait s'échapper. En fait, ce résultat correspond à une distribution électronique trop schématique. En effet:

a) Les données récentes de NEWKIRK [31] montrent que les densités coronales en période de maximum solaire doivent être multipliées par un facteur important, peut-être de l'ordre de 4 par rapport à celles données par la formule de Baumbach-Allen.

b) Un modèle récent de chromosphère proposé par ATHAY [32] dépendant de 5 paramètres (proportion d'éléments chauds et d'éléments froids, densité et température électronique dans chaque élément) rend bien compte des observations sur 4 mm, 8.6 mm, 3 cm, 10 cm, 21 cm et de la variation centre-limbe sur 8.6 mm. Il semble donc que la chromosphère solaire soit beaucoup plus hétérogène que ne l'indique la formule simple utilisée.

Il est donc évident que la question devrait être réétudiée en tenant compte des inhomogénéités chromosphériques et coronales et des champs magnétiques. De plus, les courbes de variation centre-limbe observées peuvent être sérieusement affectées par le profil instrumental, comme le montrent d'ailleurs les résultats de SMERD (cf. J. P. WILD: *Solar Radio Interferometry*, ce volume, p. 282).

7. - Absorption et fréquence de collision.

L'émissivité, et par suite l'absorption, d'un milieu ionisé à haute température peuvent être considérées comme un résultat direct des *collisions électroniques*. Considérons, en effet, un électron dévié dans sa trajectoire et subissant une accélération. La formule de Hertz montre alors qu'une énergie est envoyée à l'infini par radiation dipolaire. La déviation peut provenir d'une rencontre entre un électron et un autre électron, ou bien d'une rencontre entre un électron et un ion. Dans le premier cas (masses égales), les deux radiations dipolaires se retranchent parce que les accélérations des particules sont égales et opposées et il ne subsiste plus qu'une faible radiation quadrupolaire. Dans le second cas, elles s'ajoutent mais comme l'ion est relativement lourd et immobile, seule la radiation de l'électron intervient. De même, les collisions ion-ion sont inopérantes: si les masses sont égales, il n'y a pas de radiation dipolaire; le cas des masses inégales n'est pas efficace parce que les accélérations sont trop faibles.

Le mécanisme peut être interprété en théorie classique ou bien en théorie quantique.

a) *En théorie classique*, on développe l'onde émise en intégrale de Fourier; par l'application du théorème de Parseval, on met en évidence le spectre de fréquence qui reproduit les circonstances du mouvement accéléré. Il suffit alors d'effectuer une intégration à la distribution des vitesses et à celle des orientations d'orbite et des paramètres d'impact (cf. DE JAGER, ce volume, p. 313), pour obtenir l'émissivité ϵ_ν ou puissance rayonnée par Hz par cm^3 dans toutes les

directions. L'application du principe de Kirchhoff

$$\frac{\varepsilon_\nu}{4\pi} = K'_\nu B_\nu(T),$$

fournit finalement le coefficient linéaire d'absorption

$$K'_\nu = \frac{1}{cn} \frac{8}{3} \sqrt{\frac{\pi}{6}} \frac{Z^2 e^6 g N_i N_e}{(m k T_e)^{\frac{3}{2}} \nu^2}.$$

La présence de $1/n$ dans cette relation résulte du fait que ε_ν est proportionnelle à l'indice n tandis que B_ν est proportionnelle à n^2 ; N_i et N_e sont respectivement les densités ionique et électronique; g est le facteur de Gaunt

$$g = \frac{\sqrt{3}}{\pi} \log \frac{p_a}{p_b},$$

p_a et p_b représentant des limites choisies un peu arbitrairement lors de l'intégration par rapport aux paramètres d'impact afin d'éviter la divergence de l'intégrale $\int dp/p$. Ceci constitue une grande difficulté, liée à l'extension infinie du champ coulombien. En fait, la limite inférieure est la distance minimum où l'électron peut encore être envisagé comme libre dans le champ de l'ion. La limite supérieure est plus arbitraire parce qu'elle correspond à la distance de blindage (l'électron doit continuer à former un système avec son « propre » ion). Le choix des paramètres limites d'impact pose clairement le problème des proximités. Heureusement, le facteur de Gaunt varie lentement en fonction de N_e et T_e .

b) *En théorie quantique*, la question se pose d'une manière un peu différente. On envisage l'émission ou bien comme résultant d'une transition free-free (transition entre niveaux non quantifiés d'un système ion-électron libre), ou bien comme une « bremsstrahlung » au sens de la théorie quantique des champs. Rappelons que dans cette dernière interprétation, l'électron libre est entouré d'une atmosphère de photons « virtuels »; certains photons sont réalisés par transition et la trajectoire de l'électron est en même temps déviée. On peut encore envisager le processus comme une diffusion radiative d'un électron par un champ coulombien, ou comme une absorption continue de radiation par un système électron-ion, etc. La section efficace d'absorption, définie par ion et par électron de vitesse v à l'infini est

$$a(FF) = \frac{4\pi Z^2 e^6}{3\sqrt{3} h c m^2 v} \frac{1}{\nu^3} \text{ (cm}^{-5}\text{)}.$$

Cependant, pour obtenir des résultats cohérents avec la théorie classique, il faut multiplier $a(FF)$ par $1/n$ dans un milieu réfringent.

La suite du calcul est classique: multiplier par N_i et par $dN_e(v)$, ceci représentant la distribution des vitesses v ; la distribution maxwellienne est adoptée:

$$dN_e(v) = N_e \frac{4\pi m^3 v^2 dv}{(2\pi m k T_e)^{\frac{3}{2}}} \exp \left[-\frac{mv^2}{2kT_e} \right].$$

Ensuite, par intégration sur v

$$K_v = \frac{8}{3} \sqrt{\frac{\pi}{6}} \frac{Z^2 e^6 N_i N_e}{h c m^{\frac{3}{2}} (k T_e)^{\frac{3}{2}}} \cdot \frac{1}{n v^3}.$$

Ceci représente le coefficient linéaire d'absorption, non corrigé de l'émission induite. Pour tenir compte des effets de proximité, il convient de multiplier par le facteur de Gaunt

$$g = \frac{\sqrt{3}}{\pi} \log \left(\frac{4kT_e}{e^2 N_e^{\frac{1}{3}}} \right).$$

Pour tenir compte de l'émission induite, il convient encore de multiplier par le facteur $(1 - \exp[-h\nu/kT_e])$ qui se réduit ici à $h\nu/kT_e$ aux ondes longues.

On obtient ainsi le coefficient linéaire d'absorption

$$K'_v = \frac{1}{cn} \frac{8}{3} \sqrt{\frac{\pi}{6}} \frac{Z^2 e^6 g N_i N_e}{(m k T_e)^{\frac{3}{2}} v^2},$$

qui doit être introduit dans l'équation de transfert.

On observe ici les difficultés successives. La théorie est peu naturelle. L'introduction du facteur de Gaunt pose les mêmes problèmes en théorie quantique qu'en théorie classique. La question a été récemment clarifiée par un travail de I. P. GRANT [33].

La présence de T_e au dénominateur ne signifie pas que l'absorption devient énorme aux basses températures; en fait, les électrons recombinent suivant la formule de Saha; s'il n'y a qu'une sortie d'ions

$$K'_v = \frac{32\pi^2 Z^2 e^6}{3\sqrt{3} h^3 c n} \cdot \frac{n_i}{u} g \frac{N}{v^2} \exp[-\chi/kT_e],$$

où N désigne le nombre d'atomes neutres, χ le potentiel d'ionisation et n_i et u les sommes d'état. Pour T_e tendant vers zéro, l'absorption devient nulle.

Si l'on identifie le présent coefficient d'absorption à celui trouvé à la Sec-

tion 4 par la théorie de Lorentz, on obtient la fréquence de collision:

$$\nu_c = \frac{4}{3} \sqrt{\frac{\pi}{6}} \frac{8\pi^2 m Z^2 e^4}{(mkT_e)^{\frac{3}{2}}} \varepsilon_0 g N_i.$$

Nous reviendrons à la Section 10 sur les modifications impliquées par la présence d'un champ magnétique extérieur.

8. - La variation centre-limbe calculée.

La plupart des auteurs ont adopté la symétrie sphérique. Les calculs ont été effectués par UNSÖLD, SCHLÜTER, WALDMEIER-MULLER, BURKHARDT-SCHLÜTER, NICOLET, DENISSE, SMERD, HAGEN, REULE, etc. [34] à [46], et [25]. Ces auteurs ont admis généralement une température coronale constante, le modèle de Baumbach revisé, la formule de Cillié-Menzel pour la chromosphère. La variation centre-limbe est représentée aux diverses fréquences par la Fig. 32.

On constate qu'aux ondes métriques (3 m), il y a obscurcissement centre-limbe et que le Soleil radioélectrique est plus étendu que le disque optique. Déjà à 200 MHz apparaît un anneau brillant situé à l'intérieur du disque optique. Cet anneau brillant s'accroît et se rapproche du limbe quand la fréquence croît jusque 1200 MHz environ. Il s'atténue ensuite et, aux ondes centimétriques, le disque du Soleil tend à devenir uniforme.

En fait, cette distribution est schématique:

a) En premier lieu, la température coronale ne doit pas être uniforme, les mesures de RYLE, O'BRIEN et BELL [47, 48] ayant montré que N_e et T_e

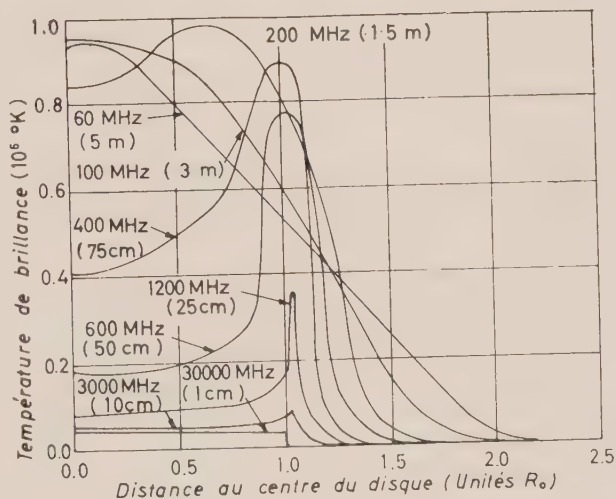


Fig. 32. - Température de brillance du disque solaire à diverses fréquences, en fonction de la distance au centre pour la composante thermique (SMERD, 1950).

varient de la manière suivante à grande distance du limbe:

$$N_e = 1.6 \cdot 10^{-8} R^{-5}; \quad T_e = 2 \cdot 10^{-6} R^{-3} (^{\circ}\text{K}).$$

b) Les densités électroniques données par la formule de Baumbach ne doivent pas être exactes à grande distance puisque les éclipses de la Crab Nebula par la couronne montrent encore une densité électronique $N_e \simeq 10^{-5} \text{ cm}^{-3}$ à 5 rayons solaires du centre.

c) Les irrégularités coronales visibles sur les photographies optiques doivent jouer un certain rôle.

d) La couronne est composée à grande distance d'éléments diffusants, comme le montre l'élargissement de la Crab Nebula éclipsee.

e) De plus les champs magnétiques coronaux au-dessus des centres d'activité modifient appréciablement l'indice de réfraction et introduisent une biréfringence.

f) Enfin, il est peu probable que les courbes de variation centre-limbe observées correspondent à la réalité.

9. — La variation centre-limbe observée.

D'une manière plus générale, il convient d'envisager le problème de la distribution de brillance car la symétrie sphérique est loin d'être réalisée.

Deux méthodes d'observation sont efficaces: a) la méthode des éclipses; b) celle des interféromètres ou des faisceaux étroits.

a) *Observations d'éclipses radioélectriques.* L'occultation progressive du Soleil par le disque lunaire fournit l'équation suivante (Fig. 33):

$$\int_{L(t)} I_r dx \cdot dy = 1 - \varphi(t),$$

$\varphi(t)$ étant le flux résiduel exprimé en pour-cent du flux total et I_r désignant la brillance normalisée.

En principe, il est possible de résoudre l'équation intégrale obtenue. Plusieurs objections sont rencontrées cependant: a) les éclipses sont rares et ne fournissent d'informations qu'à un moment dont on n'est pas maître; en particulier, le Soleil peut être actif; b) une station de campagne n'est pas un lieu propre à maintenir un radiomètre dans les meilleures conditions de fonction-

nement; or, la précision des mesures doit être élevée; en particulier, lors de la résolution de l'équation intégrale, les erreurs d'observation interviennent cumulativement; c) une courbe d'éclipse ne suffit pas; I_ν est une fonction de deux variables et ne pourra être extraite de $\varphi(i)$, fonction d'une seule variable; en

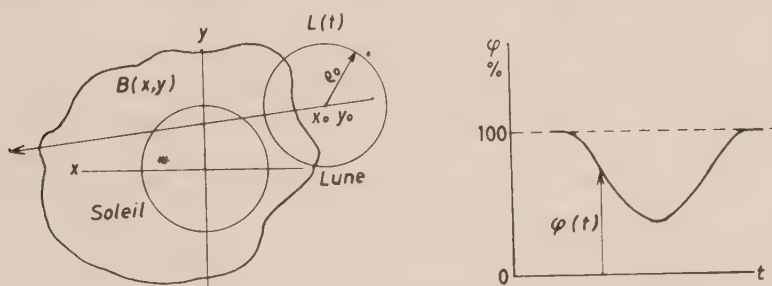


Fig. 33. — Eclipse solaire schématisée, et courbe d'occultation.

principe, les informations données par l'éclipse se limitent à la zone balayée par la Lune; d) des informations supplémentaires demandent une observation en plusieurs stations; deux ou trois stations bien localisées sont évidemment préférables; dans ce cas, les mesures doivent de préférence être faites au moyen de radiotélescopes identiques, sur la même fréquence; il est toutefois difficile d'obtenir l'homogénéité désirable; e) les réflexions sur le sol sont très gênantes; pour les éliminer, il faut comparer la courbe d'éclipse aux diagrammes obtenus pendant plusieurs journées avant et après l'éclipse; pendant ce temps, le flux du Soleil peut avoir varié.

En subdivisant la région balayée en N régions partielles de brillance supposée uniforme, l'équation intégrale se réduit à un système de N équations à N inconnues, en principe résoluble. Cependant, si l'on désire une certaine finesse, B doit être élevé (exemple: $N = 48$). Comme les erreurs instrumentales interviennent cumulativement, la méthode échoue pour ce grand nombre d'inconnues même en utilisant les plus puissantes calculatrices électroniques.

Une autre méthode n'impliquant aucune hypothèse sur la distribution coronale et permettant d'utiliser plusieurs courbes d'éclipses simultanées (obtenues en plusieurs stations) consiste à développer I_ν en série de polynômes orthogonaux (polynômes d'Hermite) sous la forme suivante:

$$I_\nu = \exp [-(x^2 + y^2)] \sum \sum a_{mn} H_m(x) H_n(y),$$

en sorte que l'équation intégrale se réduit à

$$\sum \sum a_{mn} \int_{L(t)} \exp [-(x^2 + y^2)] H_m(x) H_n(y) dx dy = 1 - \varphi(t).$$

Les intégrales peuvent être calculées directement à partir des données géométriques de l'éclipse. Appliquée à divers instants t_i , la relation précédente fournit un nombre élevé d'équations linéaires. Les coefficients a_{mn} ainsi que les erreurs probables sur ces coefficients peuvent alors être calculés par la méthode des moindres carrés. Une telle méthode a été appliquée à l'éclipse radioélectrique du Soleil calme le 30 Juin 1954 [49].

Néanmoins, la méthode des éclipses paraît dépassée actuellement, du moins sur ondes métriques, par celle des interféromètres. Les observations d'éclipse les moins sujettes à caution semblent bien être confinées aux longueurs d'onde décimétriques et centimétriques. Aux longueurs d'onde décimétriques, elles sont déjà fortement influencées par la composante provenant de sources localisées. Enfin, la question du « pouvoir résolvant » donné par les mesures d'éclipses et la perte correspondante de fréquences spatiales, n'ont pas été investiguées à notre connaissance.

b) *Méthode interférométriques.* Un exposé des méthodes interférométriques en Radioastronomie est prévu dans ces conférences. Nous n'insisterons donc pas (voir article de J. P. WILD, ce volume, p. 282).

c) *Résultats.*

1) Aux ondes millimétriques, le problème chromosphérique intervient. La chromosphère solaire paraît composée d'éléments froids (spicules) et d'éléments chauds (couronne interspiculaire). Les observations du 30 Juin 1954 faites par HAGEN sur 8.5 mm ont permis d'établir un premier modèle de chromosphère radioélectrique, en bon accord avec les observations optiques [50].

2) Aux ondes centimétriques, la présence d'un anneau brillant est confirmé par les mesures de HADDOCK en 1952 et 1954 sur 9.4 cm [51]; l'anneau brillant apparaît plus intense en 1952 qu'en 1954 (minimum solaire). Aux fréquences les plus élevées du domaine, le Soleil est circulaire, confirmant ainsi la symétrie sphérique de la chromosphère et de la très basse couronne. Aux fréquences moins élevées, l'éclaircissement centre-limbe est *équatorial*; peu d'éclaircissement est observé dans la direction des pôles.

3) Aux ondes décimétriques, les mesures montrent des plages équatoriales, brillantes et une ellipticité marquée (mesures de O'BRIEN sur 60 cm, mesures de CHRISTIANSEN sur 21 cm). Il y a peu ou pas d'éclaircissement polaire [52, 53].

4) Aux ondes métriques, léger renforcement équatorial aux ondes les plus courtes du domaine, Soleil elliptique plus étendu que le disque optique. Aux ondes les plus longues, Soleil elliptique mais pas d'anneau brillant. Sur 7.9 m, la couronne est elliptique et trois fois plus étendue que le disque optique; en même temps, un assombrissement vers l'extérieur est observé.

En résumé, l'accord avec la théorie est assez satisfaisant dans l'ensemble. Les résultats obtenus confirment l'origine thermique de la composante de base.

Une meilleure interprétation pourrait sans doute être obtenue en introduisant explicitement la symétrie non sphérique. Cependant, les résultats peuvent varier de jour en jour sous l'influence de la composante à variation lente.

Les mesures centimétriques donnent une meilleure interprétation de la chromosphère. En tout cas, ils confirment la montée rapide de la température dans la zone précoronale (sommet des spicules). Les observations sur ondes métriques montrent que la couronne est plus dense que ne le prévoit la formule de Baumbach révisée.

Un modèle précis paraît donc assez difficile à établir. Pour la chromosphère, il est nécessaire de tenir compte de plusieurs constituants. Pour la couronne, les irrégularités optiques, la diffusion, les champs magnétiques devraient être pris en considération.

10. — Influence d'un champ magnétique extérieur.

En présence d'un champ magnétique extérieur, le milieu ionisé devient biréfringent et sa radiation est généralement polarisée. L'équation du mouvement de l'électron par rapport à l'ion est donnée à la Section 3. Ici, $\mathbf{H}$ désigne le champ magnétique extérieur et l'on ne peut pas négliger le second terme de la force de Lorentz. Pour $\mathbf{E} = \mathbf{E}_0 \exp [i\omega t]$, $\mathbf{v} = \mathbf{v}_0 \exp [i\omega t]$, $\mathbf{r} = \mathbf{r}_0 \exp [i\omega t]$ et $\mathbf{r}_0 = \mathbf{v}_0/i\omega$. L'équation du mouvement devient

$$(i\omega + \nu_c)\mathbf{v}_0 + \mathbf{v}_0 \times \boldsymbol{\omega}_H = -\frac{e}{m} \mathbf{E}_0,$$

avec

$$\boldsymbol{\omega}_H = \mu_0 \frac{e\mathbf{H}}{m},$$

$|\omega_H|$ est la fréquence de cyclotron (gyrofréquence ou fréquence gyromagnétique).

Soit $\mathbf{H}$ dans la direction z . Comme $\mathbf{D} = \varepsilon_0 \mathbf{E} - N_e e \cdot \mathbf{r}$ on observe aisément qu'il existe une dépendance linéaire entre les composantes de $\mathbf{D}$ et celles de $\mathbf{E}$. La permittivité du milieu devient tensorielle

$$D_x = \varepsilon_{xx} E_x + \varepsilon_{xy} E_y + \varepsilon_{xz} E_z, \quad \text{etc.}$$

En posant

$$\alpha = \frac{\omega_p^2}{\omega}, \quad \beta = \frac{\omega_H}{\omega}, \quad \gamma = \frac{\nu_c}{\omega},$$

avec $\omega_p = \sqrt{N_e} e^2 / \varepsilon_0 m$, on trouve

$$\left\{ \begin{array}{l} \varepsilon_{xx} = \varepsilon_0 \left(1 + \alpha^2 \frac{1 - i\gamma}{(i + \gamma)^2 + \beta^2} \right), \quad \varepsilon_{xy} = \varepsilon_0 \frac{i\alpha^2\beta}{(i + \gamma)^2 + \beta^2}, \quad \varepsilon_{xz} = 0, \\ \varepsilon_{yx} = -\varepsilon_{xy}, \quad \varepsilon_{yy} = \varepsilon_{xx}, \quad \varepsilon_{yz} = 0, \\ \varepsilon_{zx} = 0, \quad \varepsilon_{zy} = 0, \quad \varepsilon_{zz} = \varepsilon_0 \left(1 - \frac{\alpha^2}{1 - i\gamma} \right). \end{array} \right.$$

Il est facile de déterminer les directions principales de polarisation. Ce sont les directions pour lesquelles $\mathbf{D}$ est parallèle à $\mathbf{E}$. A ces directions principales correspondent les valeurs propres du tenseur ε , et par conséquent les indices de réfraction principaux du milieu. Les valeurs propres sont données par

$$\det(\varepsilon_{ik} - \varepsilon_0 \lambda \delta_{ik}) = 0 \quad (i, k = 1, 2, 3; x^1 = x, \text{ etc.})$$

et valent

$$\lambda = \left\{ 1 - \alpha^2 \frac{1 \pm \beta - i\gamma}{(1 - \beta^2) - \gamma(2i + \gamma)} \right\}, \quad \lambda = \left\{ 1 - \alpha^2 \frac{1}{1 - i\gamma} \right\}.$$

En développant en séries ces expressions par rapport à γ et en identifiant au premier ordre en γ avec le carré de l'indice complexe

$$n = n' - i \frac{cK}{2\omega},$$

on trouve aisément les indices de réfraction principaux et les coefficients principaux d'absorption

$$\left\{ \begin{array}{l} n = \left(1 - \frac{\alpha^2}{1 \mp \beta} \right)^{\frac{1}{2}}, \quad K = \frac{\omega \alpha^2 \gamma}{nc} \frac{1}{(1 \mp \beta)^2}, \\ n = (1 - \alpha^2)^{\frac{1}{2}}, \quad K = \frac{\omega \alpha^2 \gamma}{nc}. \end{array} \right.$$

Les directions principales de polarisation sont fournies par

$$\sum_k (\varepsilon_{ik} - \varepsilon_0 \lambda \delta_{ik}) E_k = 0.$$

a) Pour les deux premières valeurs propres:

$$\pm E_x + i E_y = 0, \quad -i E_x \pm E_y = 0, \quad E_z = 0.$$

Il s'agit d'une onde propagée suivant l'axe du champ magnétique. Le calcul des paramètres de Stokes (cf. Première Partie, I, Section 3) indique que

$$P = Q, \quad R = 0, \quad S = \mp P.$$

La radiation est donc polarisée *circulairement* (à gauche pour la première valeur propre et à droite pour la seconde).

b) Pour la troisième valeur propre:

$$E_x = E_y = 0, \quad E_z \neq 0.$$

Il s'agit d'une onde propagée *perpendiculairement* à la direction du champ magnétique. Cette onde a une polarisation *rectiligne*.

On constate qu'il existe ici trois indices de réfraction principaux (accompagnés de coefficients d'absorption correspondants). Explicitement:

$$\begin{cases} n_o = \left(1 - \frac{\omega_p^2}{\omega^2}\right)^{\frac{1}{2}}, & n_e = \left(1 - \frac{\omega_p^2}{\omega(\omega \mp \omega_H)}\right)^{\frac{1}{2}}, \\ K_o = \frac{\omega_p^2 \nu_c}{\omega^2 n_o c}, & K_e = \frac{\omega_p^2 \nu_c}{(\omega \mp \omega_H)^2 n_e c}. \end{cases}$$

Le couple n_o, K_o correspond à la même radiation qu'en l'absence de champ magnétique (cf. Section 3); cependant, la radiation est propagée ici perpendiculairement au champ, et à polarisation rectiligne.

Les couples n_e, K_e correspondent à une radiation circulaire propagée suivant le champ. Comme les coefficients d'absorption sont différents pour les deux composantes circulaires, on doit s'attendre à une émission de radiation polarisée par la couronne solaire en présence de champs magnétiques. Pour cette radiation, il y a deux fréquences critiques (indice nul)

$$\omega_{cr} = \frac{1}{2} \left\{ \sqrt{4\omega_p^2 + \omega_H^2} \pm \omega_H \right\},$$

et par conséquent, deux altitudes minima de formation. En général, l'altitude minimum extraordinaire est plus grande que l'altitude minimum ordinaire, cette dernière correspondant à un coefficient d'absorption plus faible et par conséquent à une moindre émissivité.

Observons encore que pour une direction de polarisation ne correspondant pas à une direction principale, l'onde propagée est à polarisation elliptique.

En conséquence, pour des champs magnétiques dirigés vers l'observateur, la radiation doit comprendre une composante circulaire. Pour des champs

ondes métriques dans une accumulation de sursauts brefs et intenses (orage radiosolaire).

Une analyse plus détaillée des enregistrements à fréquence fixe montre divers types de sursauts qu'on peut classer suivant leur aspect à chaque longueur d'onde. Ainsi un sursaut abrupt aux ondes métriques apparaît le plus souvent adouci aux ondes centimétriques. Un même sursaut peut être visible sur tout le spectre; d'autres sont limités à d'étroits domaines spectraux. Deux types de sursauts au moins présentent une dérive de fréquence, en ce sens qu'ils apparaissent plus tôt aux ondes courtes qu'aux ondes longues et se terminent plus tôt. Deux types au moins sont polarisés circulairement, ce qui indique l'influence d'un champ magnétique. Enfin, la soudaineté des phénomènes, leur grande intensité, excluent souvent l'hypothèse d'une origine thermique; il semble donc bien que, pour les transitoires, la radiation non thermique soit de règle et que la radiation thermique représente l'exception.

Il apparaît clairement aussi qu'une étude détaillée des radiations transitoires impliquerait des mesures simultanées *d'intensité* en fonction de la *fréquence*, du *temps*, du *lieu* dans l'atmosphère solaire et de la *polarisation*. Les enregistrements panoramiques (radiospectrogrammes) fournissent l'intensité en fonction de la fréquence et du temps avec une sensibilité encore assez faible. Les observations interférométriques donnent la position des sources en fonction de la fréquence et du temps, mais la polarisation, qui exige une modification de l'appareillage, n'est pas mesurée simultanément. Les observations directes de polarisation sont encore assez rares. Il n'existe actuellement aucun appareillage donnant à la fois tous les facteurs nécessaires. Comme la réalisation d'un tel instrument est hors des possibilités actuelles, il reste à comparer les mesures effectuées en divers observatoires au moyen d'instruments de types différents. C'est ce qui a été fait, jusqu'à présent, pour les enregistrements à fréquence fixe.

1. - Classification des transitoires dans les enregistrements globaux à fréquence fixe.

Trois systèmes de classification sont utilisés actuellement:

- a) Classification du *Quarterly Bulletin of Solar Activity* (CSIRO, Australie).
- b) Classification des CRPL F-Reports (Central Radio Propagation Laboratory, National Bureau of Standards, U.S.A.).
- c) Classification de Cornell University et classifications dérivées.

Ces classifications sont exclusivement descriptives et ne prétendent pas donner la signification physique du phénomène. Elles ont pour objet d'en définir une image globale, sans détails superflus, pour fixer les idées et per-

mettre la comparaison des enregistrements sans nécessiter leur échange ou l'envoi de copies.

Les enregistrements à fréquence fixe sont dépouillés comme suit:

1) Médianes trihoraires du flux (0-3, 3-6, etc., heures TU) et moyenne arithmétique journalière des médianes trihoraires (unité $10^{-22} \text{ W} \cdot \text{m}^{-2} \cdot \text{Hz}^{-1}$).

2) Variabilité, dans une échelle arbitraire 0-1-2-3 (0 = très calme, 3 = très agité); indice trihoraire et moyenne journalière.

3) Événements remarquables: heure du début et durée du phénomène, maximum instantané (pic le plus élevé au dessus du zéro) et maximum adouci (sommet le plus élevé au dessus du fond continu [sur l'enregistrement adouci]).

4) Eventuellement la polarisation (en % $= 100(D - G)/(D + G)$, D étant l'intensité de la composante droite et G celle de la composante gauche).

Le centre de Sydney (CSIRO) se charge de collationner les résultats et de les homogénéiser en vue de leur publication au *Quarterly Bulletin*. Deux autres

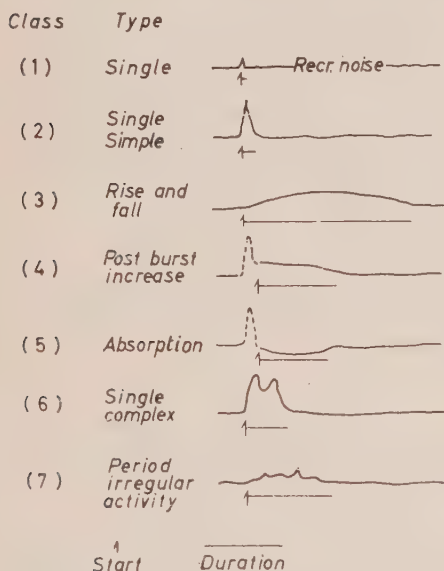


Fig. 35. — Classification des sursauts sur ondes décimétriques. (CRPL).

Classe et type des sursauts: (1) unique, au dessus du bruit de fond du récepteur; (2) unique, simple; (3) montée suivie de descente; (4) augmentation après sursaut; (5) absorption; (6) unique, complexe; (7) période d'activité irrégulière. Le début (start) et la durée (duration) sont indiqués sur le cliché par des signes conventionnels pour les divers événements.

centres fonctionnent respectivement à Boulder (CRPL) et à Moscou (NIZMIR). D'autre part, des listes miméographiées circulent entre observatoires et font l'objet de publications dans les séries propres à l'observatoire émetteur.

La classification du CRPL est résumée par les Fig. 35 et 36 qui se rapportent respectivement aux ondes courtes (classification de COVINGTON) et aux ondes longues (classification de DODSON-HEDEMAN). Observons qu'aux ondes longues augmentation de flux qui suit un sursaut (majeur ou mineur) est désignée par le symbole « plus » quand elle existe. Les mesures spectrographiques montrent qu'il s'agit en fait d'un phénomène distinct du sursaut initial quoique l'origine puisse en être commune.

La classification de Cornell University, établie par OWREN *et al.* [54] est donnée par les Fig. 37 à 40. Il s'agit d'une classification très riche, probablement surabondante.

La classification utilisée dans le *Quarterly Bulletin* est résumée au Tableau VI.

TABLEAU VI. — *Classification du Quarterly Bulletin.*

E = début soudain d'activité;
A = phénomène paraissant faire partie d'une activité générale;
D = phénomène distinct d'une activité générale ou lui paraissant superposé;
C = variation complexe d'intensité;
M = deux ou plusieurs pics séparés par des périodes calmes relativement longues;
S = simple montée du flux suivi d'une descente (rise and fall);
D = double montée du flux (peu usité);
F = groupe de sursauts (peu usité).

Les symboles littéraux peuvent être associés par deux ou trois, *E*, *M* marchent avec *S*, *C* et *A*, *D* (exemple: *ECD*).

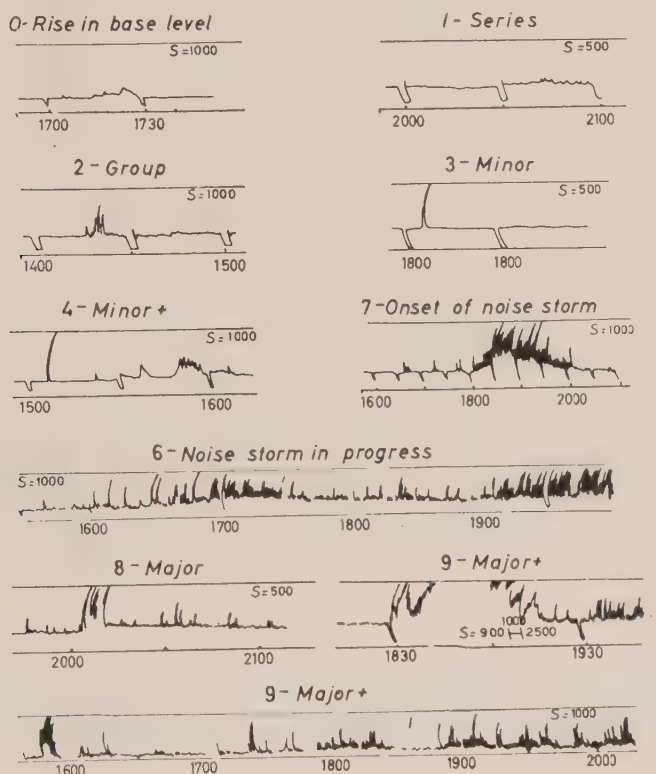


Fig. 36. — Classification des sursauts sur ondes métriques. (CRPL).

Type d'événement: (0) augmentation du niveau de base; (1) série de sursauts; (2) groupe de sursauts; (3) sursaut mineur; (4) mineur « plus »; (7) début d'orage; (6) orage en progrès; (8) sursaut majeur; (9) majeur « plus ».

La seule classification physique repose actuellement sur les mesures radio-spectrographiques. Elle n'est pas praticable par les observatoires ne disposant

que d'enregistreurs à fréquence fixe. Cependant, la comparaison d'une série d'enregistrements simultanés à diverses fréquences peut fournir des résultats physiquement intéressants tout en faisant bénéficier d'une sensibilité accrue.

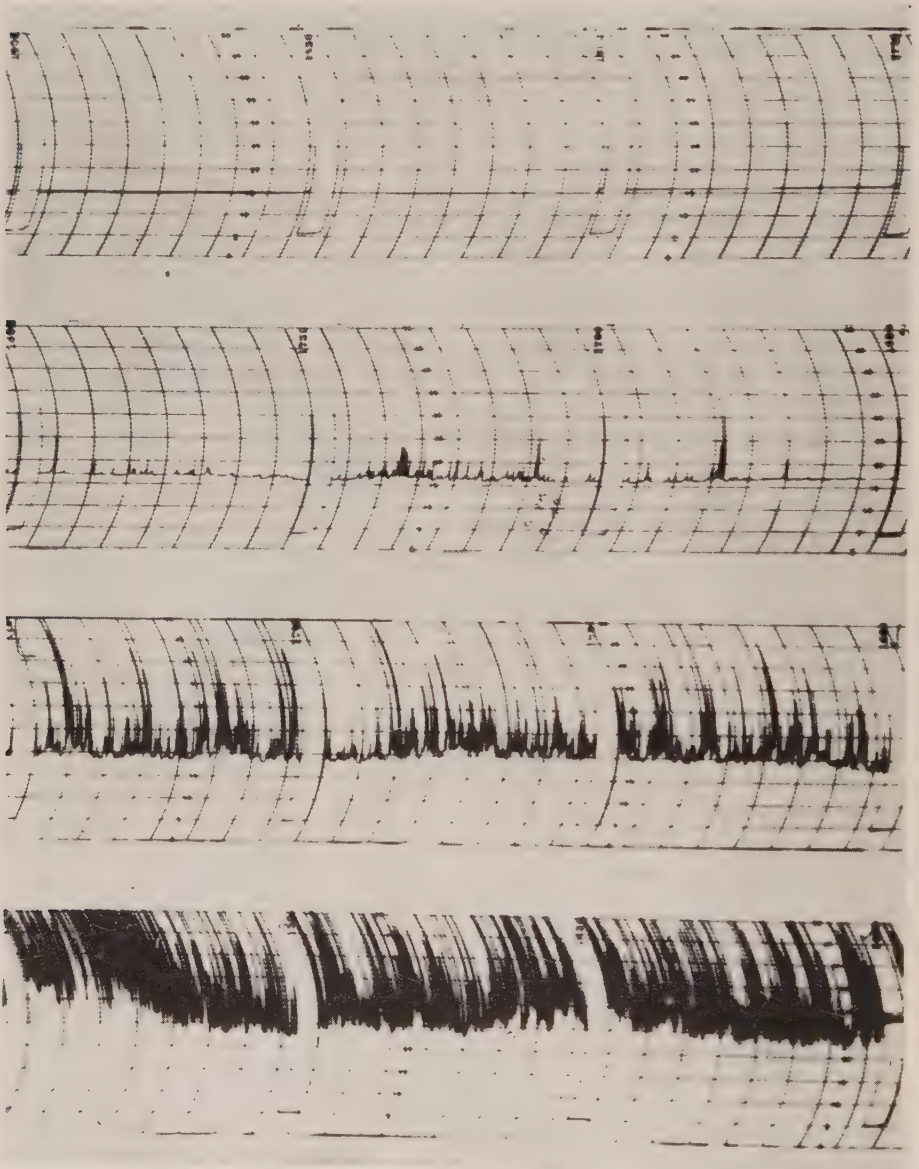


Fig. 37. — Classification de Cornell University; fréquence des sursauts.

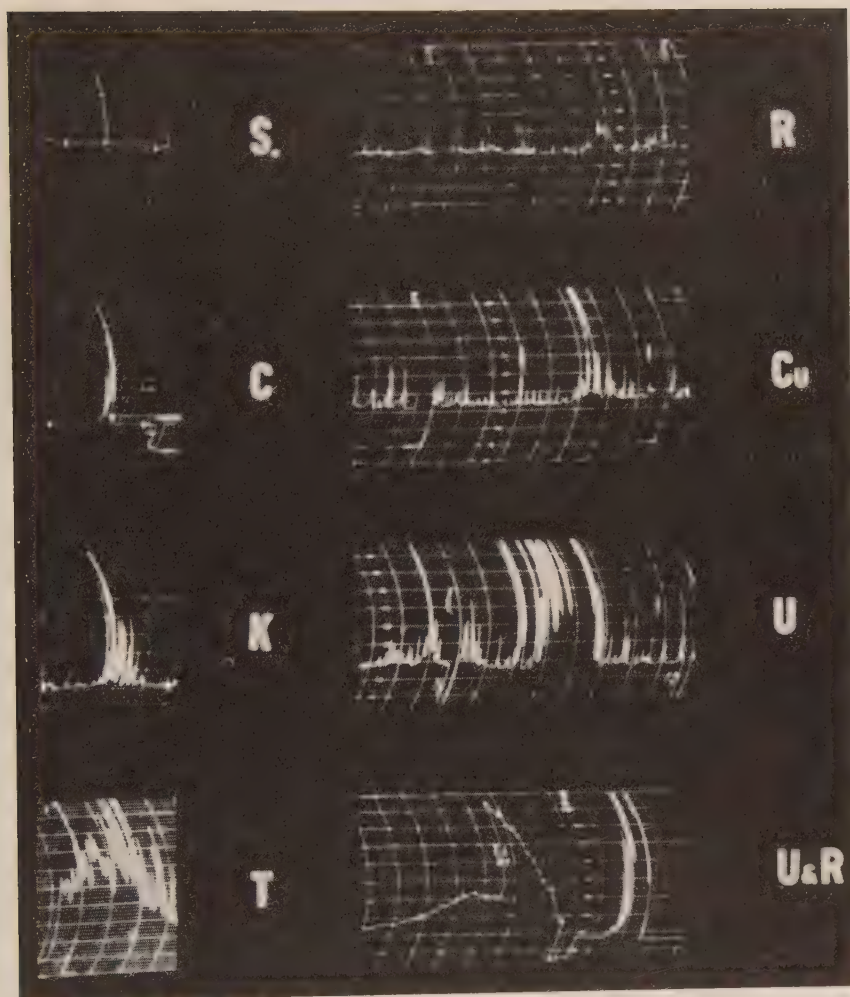


Fig. 38. — Classification de Cornell University; événements remarquables.

2. — Transmission rapide des informations radioélectriques solaires.

Un examen détaillé de l'activité solaire exige la mise en correspondance des observations optiques, radioélectriques, et celles ayant trait aux phénomènes géophysiques associés (ionosphère, géomagnétisme, aurores, rayons cosmiques, sifflements, propagations, etc.). D'autre part ces observations sont nécessaires pour la conduite des techniques (radiocommunications, etc.). Il en résulte qu'une transmission immédiate des données a été organisée, déjà à partir

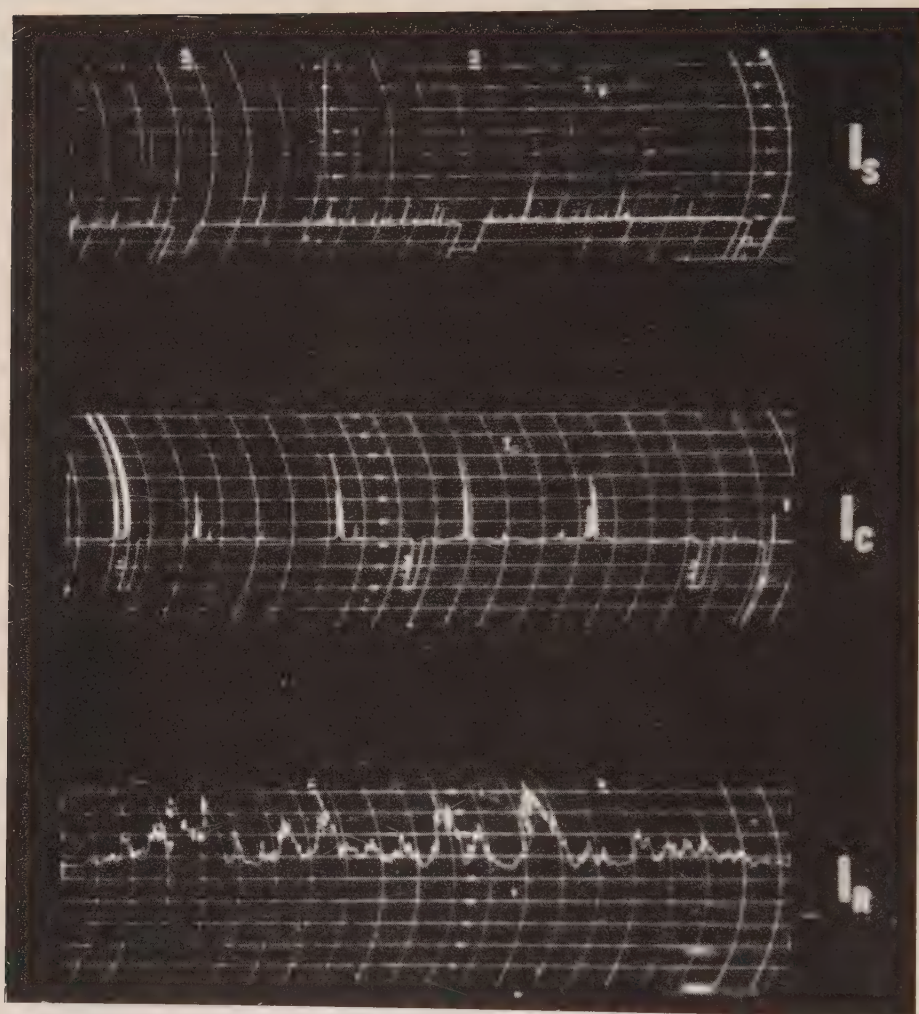


Fig. 39. — Classification de Cornell University; événements remarquables (suite).

de 1931, et a pris une grande importance au cours de l'Année Géophysique Internationale.

Actuellement, les données radioélectriques solaires sont centralisées et disséminées parmi les observatoires et les utilisateurs par le Service international des Ursigrammes. Dans cette organisation, on a partagé la Terre en quatre groupements régionaux constituant des réseaux (Europe-Afrique, Eurasie, Pacifique occidental, Hémisphère occidental); chaque réseau est pourvu d'un ou plusieurs centres de rassemblement et de dissémination des données, disposant de moyens de communication radiotélégraphiques et télégraphiques (téllex).

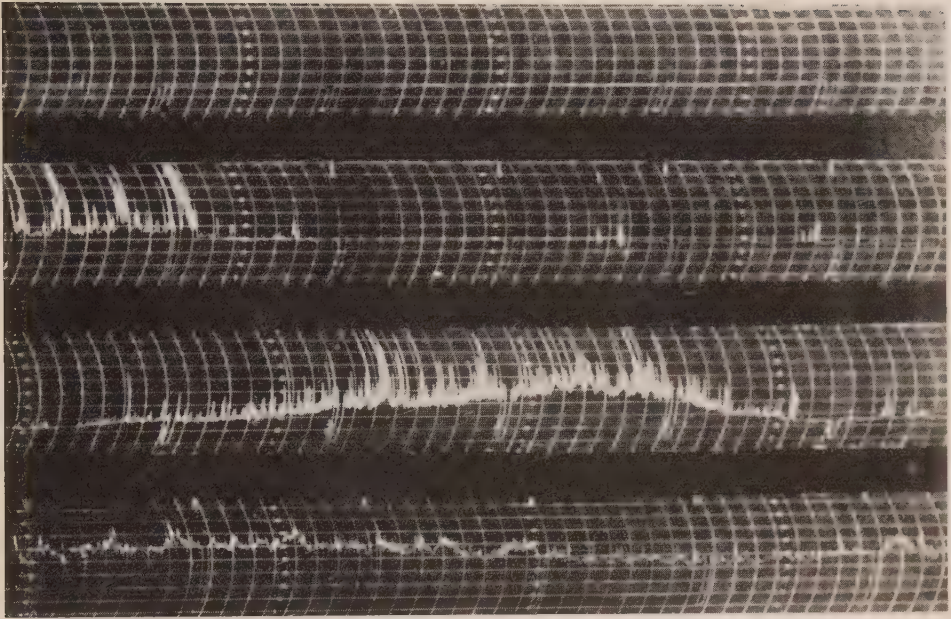


Fig. 40. — Classification de Cornell University; événements remarquables (suite).

Ces centres communiquent entre eux, et avec les observatoires qui leur envoient les données. Les communications par télex sont évidemment les plus adéquates. Il en résulte que tous les observatoires participants sont en mesure de recevoir les données qui les intéressent à l'échelle *planétaire*.

Les messages sont émis sous forme codée. Chaque code est désigné par un mot-clé, et contient un certain nombre de groupes de 5 chiffres résumant les observations. Il existe également des codes d'avertissement. Les informations émises ne se limitent pas aux observations radioélectriques solaires mais couvrent l'activité optique, les influences ionosphériques, géomagnétiques, aurorales, ainsi que divers autres domaines géophysiques. Un manuel des codes est publié par le Secrétariat général de l'URSI. Plus de 130 observatoires participent actuellement au service.

3. — Classification radiospectrographique.

Une description des méthodes radiospectrographiques est donnée par J. P. WILD [55]. Rappelons-en le principe: dans un radiospectrographe, le signal d'antenne est reçu par un amplificateur accordé sur une fréquence rapidement variée en fonction du temps (récepteur panoramique); le signal de

sortie de l'amplificateur est envoyé après détection au circuit de grille d'un tube à écran cathodique et fournit une image lumineuse ponctuelle dont l'intensité est proportionnelle à celle du signal d'antenne; cette image est déviée sur l'écran de manière que son ordonnée (y) soit proportionnelle à la fréquence d'accord (par convention, les hautes fréquences sont situées vers le bas), tandis que son abscisse (x) soit proportionnelle au temps. De cette façon, les sections verticales de l'image sont les spectres instantanés, et les sections horizontales correspondent à des enregistrements à fréquence fixe. L'image d'un sursaut

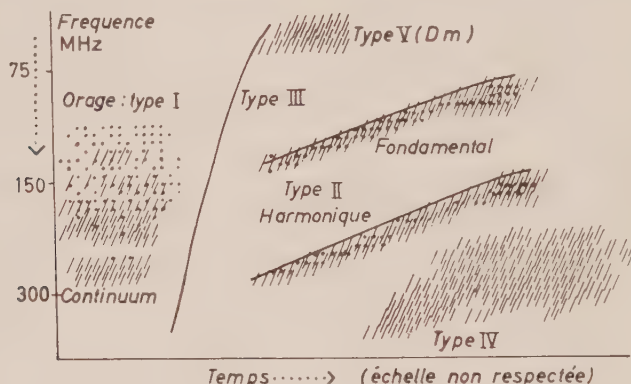


Fig. 41. — Radiospectrogrammes typiques: sursauts de type I, II, III et IV.

sur l'écran constitue son « spectre dynamique ». La Fig. 41 résume les divers types spectrographiques de sursauts. On y distingue:

a) Les sursauts d'orage ou sursauts de type I, apparaissant aux fréquences métriques sous la forme de *points* groupés en *nuage* agité et fluctuant, dans une région relativement fixe en fréquence et étendue sur un large intervalle de temps.

b) Les sursauts de type II, ou « grands sursauts », se présentant sous la forme d'un domaine allongé, assez faiblement incliné, le début du phénomène ayant lieu plus tard aux fréquences basses. De tels sursauts sont souvent accompagnés d'harmoniques à une fréquence double ce qui indique une émission non linéaire ou un phénomène non linéaire de plasma.

c) Les sursauts de type III, ou « sursauts isolés », se présentant sous la forme d'un domaine très incliné, sans grand retard aux fréquences basses. Cette circonstance est très importante car s'il s'agit d'une émission sur une longueur d'onde croissant avec l'altitude, la source de la radiation doit s'élever très vite dans la couronne.

d) Les sursauts de type IV, se présentant sous la forme d'un continuum aux fréquences décimétriques et métriques, et occupant un domaine relativement stationnaire. Ces sursauts apparaissent le plus souvent consécutivement à un sursaut de type II, et en présence d'une grande éruption chromosphérique. Parfois le sursaut de type II est lui-même précédé d'un ou plusieurs sursauts de type III.

e) Les sursauts de type V, sont aux sursauts de type III ce que le type IV est au type II, mais apparaissent plutôt aux fréquences décamétriques.

f) D'autres sursauts sont encore discernables sur le radiospectrogrammes : sursauts en U inversés, sursauts en arêtes, dédoublements etc. Il semble donc bien que tout ne soit pas découvert dans cette voie et que beaucoup de progrès doivent résulter de la sensibilisation des radiospectrographes.

Grâce aux observations à fréquence fixe, aux localisations interférométriques des sources et aux données sur la polarisation, une première idée de la nature physique des transitoires radiosolaires peut se concrétiser. Les principaux résultats sont résumés dans le Tableau VII.

4. — La composante à variation lente.

Cette composante se superpose au fond continu thermique de la composante de base. En intensité, elle représente 30 % du fond continu thermique à 3 cm de longueur d'onde et 100 % à 60 cm. Elle existe vraisemblablement aux plus grandes longueurs d'onde. Aux ondes métriques, elle est souvent rendue invisible par les phénomènes à variabilité plus élevée. Il est très probable qu'elle constitue le fond continu des orages radioélectriques observés aux fréquences basses.

La composante à variation lente présente la récurrence de 27 jours caractéristique de la rotation solaire. On l'observe en présence de taches, de régions magnétiques et de plages faculaires actives. Pour une aire tachée de 5 milliardièmes du disque optique, son intensité est approximativement

$0.5 \cdot 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$	à	1.5 m de longueur d'onde
20	à	60 cm
60	à	30 cm
70	à	6 cm
76	à	3 cm

alors qu'à ces mêmes longueurs d'onde l'intensité du Soleil calme représente respectivement $7.5 \cdot 10^{-22}$, 30, 48, 160 à 124, 350 à 310. Reportées dans un

TABEAU VII. — Emissions

Nature du phénomène	Caractère de la source		Nature de la radiation	Caractères de la		
	durée	diamètre		intensité ($T \cdot K$)	variabilité	spectre
Composante de base	variation undécennale	Sup. à 32' augmente avec λ	Soleil non perturbé	10^6 augmente avec λ	nulle	mm, cm, dm, m, Dm
Composante à variation lente	plusieurs mois	1 à 10'	continuum récurrent (27 jours);	$< 2 \cdot 10^6$	nulle	(cm), dm, (m)
	jours minutes	1' 0',5	continuum « rise and fall »	$< 5 \cdot 10^5$ $< 5 \cdot 10^5$	nulle faible	(cm), dm, (m) (cm), dm, (m)
Orages radio-électriques et phénomènes correspondants	heures jours	1' 10'	continuum plus sursauts brefs de type I	$\sim 10^9$	élevée	m, (dm)
Sursauts de type I	0.01 à 0.1 s	1'	sursauts d'orage		simple, caractère ponctuel dans les spectres	m spectre très étroit
Sursauts de type II	minutes		« explosions » ou « outbursts » (slow bursts)	$> 10^{10}$ augmente avec λ	très complexe	m, Dm large (50 MHz) dérive de fréquence, coupure nette aux basses fréquences
Sursauts de type III	secondes	10' augmente avec λ	« sursauts isolés »	$> 10^{11}$ augmente avec λ	simple-parfois en groupes	dm, m, Dm large (10 MHz) dérive de fréquence, coupure peu apparente
Sursauts de type IV	minutes heures	10' croît avec λ	continuum	$\sim 10^{11}$ parfois diminue avec λ croissant	stable; lentes oscillations	cm, dm, (m) large, parfois limité aux ondes courtes

radioélectriques solaires. Résumé.

variation			
polarisation	Origine	Phénomènes associés	REMARQUES
au hasard	thermique	transitions free-free (H et He ⁺)	— limbe obscurci sur mm; — limbe brillant sur cm, dm; — soleil elliptique sur m, bord obscurci.
au hasard	thermique	taches, plages	— macrocondensations (facules);
partiellement circulaire	thermique + H	—	— condensations coronales moyennes;
partiellement circulaire	thermique + H	—	— microcondensations
circulaire	non thermique (turbulence + H)	vague association avec centres d'activité	Centres radioélectriques — déplacements lents dans la couronne; — la tache optique apparaît avant et disparaît après; — parfois exceptions dans la polarisation (variable, faible, différence pour sursauts et continuum).
totalelement circulaire	non thermique	idem	origine dans les centres radioélectriques.
généralement au hasard	non thermique (ondes de choc dans plasma)	première phase des éruptions	mouvement ascendant [(100 ÷ 3 000) km/s]; — émissions à la fréquence critique; émission de particules aurorales; émissions harmoniques associées (fréq. double); parfois dédoublements Zeeman.
généralement au hasard; parfois traces de circulaire	non thermique (oscillations de plasma?)	première phase des éruptions (précurseurs)	mouvement ascendant ($\frac{1}{5}$ à $\frac{1}{2} \times$ vitesse de la lumière); émissions de particules cosmiques; spectre intrinsèquement étroit.
circulaire généralement	non thermique (synchrotron)	dernière phase des grandes éruptions (10 à 20 min après II)	seconde partie du Majeur +; — source d'abord ascendante (type II) puis se stabilisant à grande altitude; — émissions de particules cosmiques.

TABLEAU VII (continuation).

Nature du phénomène	Caractère de la source		Nature de la radiation	Caractères de		
	durée	diamètre		intensité (T °K)	variabilité	spectre
Sursauts de type V	minutes		continuum	$\sim 10^{10}$ diminue avec λ croissant	stable	Dm
Sursauts en U inversés	$\frac{1}{2}$ min		sursauts plus continuum	croît avec λ	simple	m, Dm
Sursauts en arêtes	minutes secondes		sursauts		en groupes	id. type III
Phénomène du 4 Nov. 1958	heures	10' + centres brillants (I')	grandes oscillations, sursauts, scintillation	$\sim 10^{10}$	énormes sursauts de 0.2 à 0.3 s oscillations de 0.1 min	m très variable très étroit (absent sur d)

diagramme température équivalente-longueur d'onde, ces valeurs fournissent une courbe présentant un plateau assez large de 10 à 100 cm, et retombant rapidement au delà de 100 cm.

Les premières observations de cette composante furent faites par COVINGTON sur 2800 MHz [56], et par LEHANY et YABSLEY [57] sur 1200, 600 et 200 MHz. En fait, il existe une corrélation étroite entre les enregistrements obtenus aux hautes fréquences mais, pour 200 MHz, la corrélation est plus lâche. C'est pourquoi on limite arbitrairement le domaine de la composante en question à $(3 \div 60)$ cm.

Quand on porte en graphique l'intensité du flux du Soleil calme en fonction de l'aire tachée on obtient un diagramme montant (cf. Fig. 42), caractéristique d'une relation linéaire assez nette, et sur lequel une extrapolation à une aire tachée nulle fournit la composante de base. Cependant, CHRISTIANSEN et HINDMAN [58] ont montré que la pente de la droite de régression subit une variation séculaire: au maximum solaire, cette pente est plus forte qu'au minimum et tout se passe comme si les taches étaient radioélectriquement plus actives. Il existe également un délai entre taches et radiation; en fait la radiation semble suivre les taches et perdurer au delà de leur disparition. Comme PIDDINGTON et DAVIES [59] l'ont montré, la radiation est en retard de 2 rota-

ariation	Origine	Phénomènes associés	REMARQUES
polarisation			
circulaire?	non thermique (synchrotron)	suit les sursauts de type III	— seconde partie du Mineur +; — source ascendante (id. IV) puis stabilisée; — émissions de particules cosmiques.
	non thermique (ondes de choc)		— source ascendante puis descendante (50 000 km/s), associé aux surrections.
			— émissions de type III simultanément au type II? — source ascendantes et aussi descendantes.
totale circulaire	non thermique (inconnu)	avant éruption optique; se poursuit de nombreuses heures après	— emplacement d'une éruption d'importance 1 sur une plage faculaire ancienne; — scintillations dans la couronne?

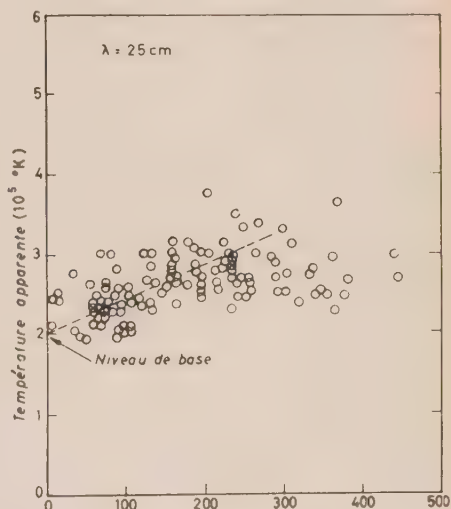
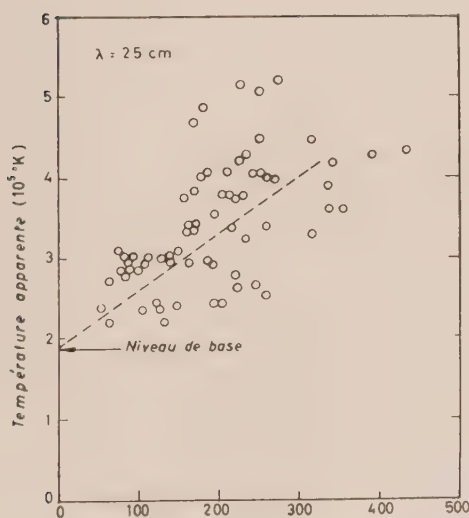


Fig. 42. — Diagrammes de dispersion donnant la température apparente à 1200 MHz en fonction de l'aire projetée des taches (en millionnièmes du disque visible). A gauche, Août-Novembre 1947; à droite, Septembre 1949 - Juin 1950 (CHRISTIANSEN et HINDMAN, 1951).

ions solaires sur les taches entre 600 et 1200 MHz; il n'y a pas de délai à 2800 MHz; pourtant, à 9400 MHz, un délai de 1 rotation a été constaté.

L'identification de la source a d'abord été faite au moyen d'observations de l'éclipses. Le 13 Novembre 1946, COVINGTON observe sur 2800 MHz la disparition d'une région brillante située au sein d'un groupe important de taches; le 1er novembre 1948, CHRISTIANSEN, YABSLEY et MILLS observant en trois stations éloignées remarquent que les aires brillantes sur 600 MHz ne correspondent pas toujours à des taches visibles; ainsi, sur 8 sources certaines, 3 correspondent à des taches, 4 à des régions occupées précédemment par des taches, 1 est située au dessus d'une protubérance [60].

Les observations interférométriques donnent maintenant des résultats plus détaillés. Il semble bien exister plusieurs types de composantes à variation lente: a) la composante de longue durée (plusieurs mois) a pour source des régions de 1 à 10' de diamètre associées à des plages faculaires actives ou *macrocondensations*; pour cette composante la température équivalente du disque est de l'ordre de $2 \cdot 10^6$ °K ou inférieure, b) la composante de durée moyenne (jours) dont la source plus étroite (1') constitue une *condensation coronale moyenne*, et dont la température équivalente est inférieure à $5 \cdot 10^5$ °K, c) enfin la composante de courte durée (minutes) de source plus étroite ($\frac{1}{2}$ ') ou *microcondensation*, et de température équivalente du même ordre que la précédente. Il est intéressant de noter que la composante de longue durée paraît polarisée au hasard tandis que les deux autres présentent des traces de polarisation circulaire.

Certains auteurs, dont WALDMEIER et MÜLLER, ont imaginé un modèle de condensation coronale à *haute température* (10^7 °K) pour expliquer les effets observés. Cependant, il faut tenir compte de la polarisation partielle circulaire ce qui peut impliquer l'existence de champs magnétiques. Les nouvelles interprétations de CHRISTIANSEN et MATHEWSON [61] montrent au contraire que les régions où la composante de longue durée est émise à 20 cm de longueur d'onde sont à peu près à la température coronale *normale* (10^6 °K) mais qu'elles sont *plus denses*; la durée est de 3 mois; l'altitude varie entre 200 000 et 100 000 km; la densité est 20 fois celle de la couronne (env. 10^8 électron/cm³).

Il convient donc de distinguer entre composante de longue durée (non polarisée) et composante de courte durée (partiellement polarisée). Pour la composante de longue durée l'émission est strictement thermique; seule intervient l'augmentation de la densité électronique dans la région large d'émission; encore faudrait-il expliquer comment la condensation peut subsister aussi longtemps en l'absence d'un agent magnétique. Pour les composantes de courte durée, l'émission n'est plus strictement thermique comme l'indiquent les traces de polarisation; les électrons s'organisent en hélices le long des lignes de force de champs magnétiques qui expliquent aussi comment la condensation peut se former. Les «gradual rise and fall», de très courte durée (quelques

minutes), seraient dûs à des condensations disparaissant très vite. D'une manière générale, les condensations ne sont pas plus chaudes que la couronne adjacente. Cependant, la formation d'une condensation coronale peut parfois être observée optiquement, dans les régions déjà denses (raie verte coronale $\lambda 5303$, $T = 10^6$ °K); l'apparition de la raie jaune $\lambda 5694$, due à Ca XV dont le potentiel d'ionisation est de 814 eV, impliquerait une température de l'ordre de 10^7 °K. Enfin l'apparition de H_α montre que la condensation s'est refroidie et est devenue beaucoup plus dense. Rappelons que les arches coronales se forment ensuite par épuisement local de la couronne, et ensuite les longs jets coronaux. Des observations faites au cours de l'éclipse du 25 Février 1957 ont montré qu'aux ondes métriques, certaines condensations peuvent être situées dans l'axe des jets, à des endroits situés au dessus de régions où la raie verte est particulièrement intense [62].

Remarquons aussi que la présence des condensations coronales rayonnant également l'ultraviolet et la radiation X permettrait d'expliquer, comme l'a montré DENISSE, la forte corrélation entre le flux radioélectrique solaire sur 2800 MHz et la densité électronique dans la couche E' de l'ionosphère.

5. - Orages radioélectriques et phénomènes associés: sursauts de type I.

Les orages radioélectriques solaires sont observés sur les longueurs d'onde de 1 à 15 mètres. Ils se caractérisent par

a) une élévation parfois très rapide du niveau, précédée souvent de courts sursauts annonciateurs;

b) un accroissement considérable d'intensité, accompagné de sursauts pouvant dépasser 100 fois le niveau de départ;

c) une accumulation de *sursauts courts* (durée 0.01 à 2 secondes), réunis à leur base vraisemblablement par suite du manque de pouvoir résolvant dans le temps des enregistreurs, et accompagnés vraisemblablement d'un *fond continu*; suivant certains auteurs, le fond continu n'est qu'apparent, cependant les enregistrements à grande vitesse au moyen de radiomètres à faible constante de temps (0.1 s) montrent souvent ce fond continu même aux ondes les plus longues du domaine métrique;

d) la radiation est fortement polarisée (circulaire), à gauche ou à droite; cette polarisation se conserve aussi longtemps que dure le phénomène; si elle varie, l'emplacement de la source varie également; il y a des irrégularités dans la distribution de la polarisation: parfois la polarisation est faible, différente pour les sursauts et le continuum;

e) la source de la radiation est localisée dans la couronne, et son association avec une tache ou un groupe de taches est parfois vague. La source

se déplace parfois lentement dans la couronne, mais sans jamais s'écarter beaucoup de sa position initiale.

Certaines analogies peuvent être relevées entre la composante orageuse (m, Dm) et la composante à variation lente (cm, dm). Par exemple, un orage observé aux longueurs d'onde métriques est accompagné d'une lente élévation du niveau aux ondes décimétriques; aux interféromètres, une source de radiation d'abord calme se transforme progressivement en une source d'orage.

Le diamètre de la source paraît compris entre 1' et 15'. Une haute température équivalente (10^9 °K) est mesurée. Les enregistrements à des fréquences voisines sont très différents, ce qui indique que le spectre des orages et particulièrement celui des sursauts, est très étroit. En fait, sur les radiospectrogrammes, les sursauts d'orage se présentent comme des points naissant dans un continuum et y disparaissant après un temps très court. De tels sursauts sont appelés « de type I »; ils peuvent se présenter en dehors de tout orage proprement dit. Sur les radiospectrogrammes, la région fréquence-temps dans laquelle l'orage est localisé est relativement stationnaire, mais parfois une très légère dérive de fréquence est observée. Le spectre est intrinsèquement très complexe.

La radiation débute souvent progressivement, mais peut s'établir tout à coup. Il faut distinguer ici entre *a*) l'établissement d'un orage dans une région observable proprement dite, *b*) l'existence d'un centre radioélectrique d'orage dans une région amenée progressivement par la rotation solaire dans la zone observable (effet de réfraction). Au bord du disque, l'altitude des centres d'orage peut atteindre plusieurs fois 100 000 km. Les centres persistent en général plusieurs jours. Il semble bien que quand un orage est suffisamment persistant ou récurrent, il commence après l'apparition au limbe Est d'une tache visible et cesse avant la disparition de la tache au limbe Ouest. Une telle circonstance peut s'expliquer également par un effet de réfraction.

Cependant, aucune théorie satisfaisante n'a été avancée jusqu'à présent pour expliquer le phénomène d'orage et les sursauts de type I. On ne voit pas pourquoi il existe des taches radioélectriques et des taches inactives. S'il s'agit d'une région magnétique le profil normal de l'indice de réfraction doit être déformé. Plusieurs interprétations ont été avancées: mouvements cohérents hydromagnétiques, émissions thermiques, mouvement turbulents d'un plasma magnétisé, effet dynamo, etc. Les mécanismes cohérents, non thermiques, semblent plus prometteurs mais la question n'est pas tranchée.

6. -- Sursauts de type II ou « explosions ».

Les explosions (outbursts) sont généralement associées aux éruptions chromosphériques. Elles consistent en transitoires à début brusque, à front raide, d'intensité énorme aux ondes métriques où la température équivalente du

disque peut atteindre 10^{10} °K. L'aspect du sursaut diffère considérablement suivant la longueur d'onde d'observation.

Aux ondes centimétriques, le sursaut apparaît souvent comme une élévation de niveau, de profil assez doux d'une durée de quelques minutes et d'une intensité ne dépassant pas 5 à 10 % du niveau de base. Aux ondes décimétriques, l'élévation du niveau est déjà plus forte (100 %) et le profil commence à se hérissier. La montée est rapide, souvent fluctuante, la descente accompagnée de grandes fluctuations; la durée est aussi plus longue (5 à 10 minutes). Aux ondes métriques, l'élévation du niveau est souvent énorme (10, 100 ou 1000 fois le niveau de départ, parfois plus), la montée est abrupte, la descente extrêmement agitée, avec des récurrences et un retour progressif au calme. Aux ondes décamétriques, le phénomène est saisissant par sa violence; il n'est pas rare d'observer des sursauts dont l'intensité soit 10^6 fois celle du niveau de départ.

Il est important de signaler *a*) que certains sursauts de ce type sont accompagnés d'une « seconde partie », polarisée, tandis que la première partie ou sursaut proprement dit n'est pas polarisée; *b*) que les observations simultanées à diverses fréquences et les spectres dynamiques montrent une dérive importante de fréquence, le phénomène se présentant plus tôt aux fréquences élevées; la dérive de fréquence est exprimée approximativement par $dt/d\nu = -4.5 \text{ s/MHz}$, où t est l'instant du début à la fréquence ν ; *c*) que très souvent les spectrogrammes montrent la présence d'une harmonique à fréquence double, dont la structure est très voisine de celle qu'a le spectre fondamental.

Pour interpréter le phénomène de dérive de fréquence, on part généralement d'un modèle coronal normal où l'indice de réfraction $n = (1 - \nu_p^2/\nu^2)^{1/2}$ avec $\nu_p^2 = 9\sqrt{N_c}$ et où le coefficient d'absorption est $K \sim 1/n$. L'émission principale doit alors avoir lieu à l'altitude h où ν est égale à la fréquence critique ν_p . Cette dernière hypothèse est conforme à la présence d'une coupure nette, observable sur les radiospectrogrammes vers les fréquences basses, et également au début soudain du phénomène. Comme N_c décroît en altitude une dérive de fréquence négative $d\nu_p/dt$ caractérise une source en mouvement ascendant dans la couronne. $d\nu_p/dh$ étant donné par le modèle conventionnel, il est facile d'en déduire dh/dt . On obtient ainsi les résultats suivants (modèle de Allen).

$h = 20\,000 \text{ km}$	$dh/dt = 100 \text{ km/s.}$
50 000	230
100 000	400
150 000	600
200 000	800
plus haut	$1\,200 \div 2\,000$

De telles vitesses ascensionnelles ont été effectivement observées aux interféromètres à lobe balayé (swept lobe ou swept frequency); effectivement, on

constate que la source est accélérée dans son passage à travers la couronne. Parfois elle peut être suivie très loin (5 rayons solaires) de son origine.

Il convient de rapprocher ici le sursaut de type II constaté lors d'une éruption, des aurores polaires et des orages géomagnétiques et ionosphériques observées 20 à 40 heures après l'éruption. Il est bien possible que le sursaut soit engendré dans la couronne ionisée, par des oscillations de plasma déclanchées par l'onde de choc qui représente l'envoi de particules aurorales. D'ailleurs, l'indice spectrale positif du spectre d'ensemble des sursauts de type II ($I \propto K\lambda^n$) est conforme à une émission *non thermique*. La présence d'harmoniques dans les spectrogrammes semble bien indiquer qu'il s'agit d'un mécanisme *non linéaire*. La structure compliquée du spectre instantané aux faibles longueurs d'onde traduit aussi le fait que le mécanisme devient complexe dans la haute couronne.

Les mesures de ROBERTS sur 65 spectres de type II ont fait découvrir une structure fine considérable: a) 50 % des spectres comportent une harmonique débutant en même temps que le fondamental et ayant la même structure; b) les traces sont parfois dédoublées au début, ce qui pourrait traduire un effet Zeeman; c) 10 % des spectres comportent des sursauts en arêtes partant vers le haut ou vers le bas; parfois on n'observe que les sursauts en arêtes, le spectre de type II étant absent; parfois aussi le spectre harmonique a ses sursauts en arêtes [63].

En résumé, le sursaut de type II semble bien être émis dans la couronne suite au passage d'un essaim de particules accélérées. Ces particules sont celles qui produisent les aurores polaires, les orages géomagnétiques et ionosphériques; la variabilité géomagnétique est maximum 2 jours après un sursaut de type II. Comme en témoigne l'apparition de la raie H_α tellurique au début d'une aurore polaire (par recombinaison) il doit s'agir de *protons* de faible énergie. Le mécanisme par lequel le sursaut est émis est encore mystérieux mais doit relever de la physique des plasmas. En tout cas, l'absence de polarisation exclut un mécanisme de synchrotron.

7. — Sursauts de type III.

De tels sursauts apparaissent également dans la première phase des éruptions chromosphériques. Ils se présentent généralement en groupes. Certains d'entre eux peuvent précéder le sursaut de type II (sursauts précurseurs). Mais ils peuvent également être émis en l'absence d'éruption visible. Leur forme est plus simple que celle du sursaut de type II, leur durée moindre (minutes), mais leur intensité parfois supérieure (température équivalente de l'ordre de 10^{11} °K). La montée rapide est suivie d'une décroissance exponen-

tielle simple. L'intervalle d'observation s'étend de 50 cm à 15 cm de longueur d'onde. Ils sont plus fréquents que les sursauts de type II.

Les spectres dynamiques indiquent une dérive de fréquence plus faible. Un tel phénomène apparaît presque simultanément aux diverses fréquences, mais avec un petit retard aux fréquences basses. En fait la dérive de fréquence est ici $dt/d\nu = -(4.5/\nu)$ s/MHz. Si par un procédé analogue à celui de la Section 6 on calcule la vitesse ascensionnelle de la source, on trouve des valeurs comprises entre 60 000 et 150 000 km/s. Il n'est donc nullement étonnant que de tels sursauts n'aient pas de correspondant optique connu.

Il semble bien que le diamètre de la source responsable du sursaut soit de l'ordre de $10'$ et qu'il augmente avec la longueur d'onde. De même, la constante de déclin du transitoire est de l'ordre de 0.6 à 1.5 s et tend à augmenter avec la fréquence ($1.04 \cdot 10^{-2} \nu_{(\text{MHz})}$).

Les sursauts de type III ne sont pas polarisés. Leur spectre dynamique est intrinsèquement étroit, mais il apparaît large (10 MHz) par suite de la grande dérive de fréquence. Il n'y a pas de coupure nette aux basses fréquences comme dans le cas du type II.

L'origine du sursaut de type III est probablement la même que celle du sursaut de type II, à quelques différences près résultant de l'envol plus rapide des particules. Si des oscillations de plasma sont déclenchées par un mécanisme transitoire, ces oscillations doivent s'amortir par collision. Dans ce cas, la constante de déclin du sursaut doit être du même ordre de grandeur que le temps de relaxation. En fait, les ordres de grandeur coïncident (1 s pour la constante de déclin, 2 s pour le temps de relaxation à l'altitude de la fréquence critique 70 MHz). Comme le spectre dynamique ne présente aucune coupure nette aux basses fréquences, il est probable d'ailleurs que l'émission ait lieu au dessus de l'altitude du niveau critique. De plus, l'intensité du transitoire tend à augmenter en fonction du temps de parcours de la source dans la couronne, ce qui indique un phénomène autoamplifié. L'harmonique 2 est également observé ce qui indique que le mécanisme d'émission est non linéaire.

De telles vitesses ascensionnelles sont compatibles avec l'envol de particules cosmiques. A la moitié de la vitesse de la lumière, l'énergie d'un proton est de l'ordre de 1 GeV. Cette énergie est trop faible pour que les particules cosmiques ainsi produites puissent franchir la barrière du champ géomagnétique; elles ne pourraient être observées qu'à très haute altitude (ballons, fusées sondes ou satellites) et à haute latitude géomagnétique. Mais elles peuvent s'accumuler autour de la Terre en formant les ceintures de VAN ALLEN. Le délai entre l'éjection solaire et l'arrivée doit être de l'ordre de 1 h 30 min. D'autre part, si une gerbe de plasma est émise par le Soleil à partir d'une région magnétique, cette gerbe doit emporter des lignes de force par figeage. Le champ résultant à l'arrivée peut être suffisant pour perturber le champ

géomagnétique aux hautes altitudes (de l'ordre de 10^{-3} G) et pour autoriser le passage vers la Terre. Aussi, une liaison entre les sursauts de type III et les irrptions de radiation cosmique est possible, surtout pour la composante secondaire neutronique.

8. — Sursauts de type IV.

Les sursauts de type IV sont de grandes élévations de niveau, à profil relativement adouci, constitués de radiation polarisée circulairement, qui suivent la plupart du temps un sursaut de type II non polarisé. La montée du phénomène sur les enregistrements à fréquence fixe est relativement lente: parfois elle est noyée dans la partie descendante du sursaut précurseur. L'élévation du niveau est considérable (température équivalente 10^{11} °K) et présente de larges oscillations avec une récurrence variable, de l'ordre de plusieurs minutes ou dizaines de minutes. La diminution du flux est assez lente et comme si la source s'éteignait. La durée du phénomène est variable, certains sursauts de type IV durent quelques minutes, certains autres peuvent durer plusieurs heures. Les mesures interférométriques montrent que la source a un diamètre de l'ordre de $10'$ et que ce diamètre augmente avec la longueur d'onde.

Sur les enregistrements à diverses fréquences fixes l'aspect du phénomène ne diffère pas considérablement suivant la fréquence; les mêmes grande oscillations se retrouvent, ainsi que l'allure lente et l'intensité élevée. Aux ondes métriques cependant, la variabilité paraît plus complexe qu'aux ondes décimétriques. L'intensité, au contraire, est souvent plus élevée aux ondes décimétriques. Sur les spectres dynamiques le sursaut de type IV se présente sous la forme d'un continuum occupant une large bande de fréquence et relativement stationnaire. Une légère dérive de fréquence est parfois observée, en accord avec les mesures de localisation. En fait, la source paraît s'élever lentement (100 km/s) dans la couronne, puis se stabiliser à une altitude parfois considérable (4 ou 5 rayons solaires du limbe), et enfin s'éteindre sur place.

De tels sursauts sont assez rares, quoiqu'au maximum solaire on puisse en observer un ou deux par mois aux longueurs d'onde décimétriques (par exemple, sur 600 MHz). Ils se produisent toujours après une éruption chromosphérique importante, parfois 10 à 20 minutes après le début optique de l'éruption. Dans certains cas, aucun sursaut n'est observé aux ondes métriques alors qu'aux ondes décimétriques le sursaut de type IV est très marqué.

Si l'on examine les spectres dynamiques on constate que l'émission à la fréquence critique fournit une altitude beaucoup trop basse dans le cas d'une atmosphère typique sans champ magnétique; l'altitude de la fréquence critique ne devient satisfaisante qu'en présence d'un champ dont l'intensité est de

l'ordre du gauss. En conséquence il ne peut s'agir d'une radiation ordinaire de plasma. En fait, la polarisation, et surtout *l'irruption de rayons cosmiques* après un sursaut de type IV, favorisent l'hypothèse d'une radiation de synchrotron, émise par des électrons relativistes en présence d'un champ magnétique. Les particules accélérées à quelques MeV seraient formées sur place, et l'on peut montrer que des champs magnétiques de l'ordre du gauss suffisent pour produire la radiation observée. Le freinage radiatif étant faible, la durée de l'émission serait alors limitée par la fréquence de collision.

Remarquons que la source ne s'élève pas toujours radialement. Dans le cas de l'éruption du 23 Mars 1958 (éruption en boucle avec passage de la matière lumineuse dans le champ magnétique de la tache), il est possible de suivre sur l'enregistrement radioélectrique sur 600 MHz les circonstances optiques de l'éruption. Observons encore qu'une radiation cosmique solaire a effectivement été observée à haute altitude et aux latitudes géomagnétiques élevées lors de cette éruption.

9. — Sursauts de type V.

Les investigations de WILD, SHERIDAN et TRENT [61] ont permis d'enregistrer la position d'un certain nombre de renforcements à bande spectrale large, souvent observés peu après ou en même temps que les sursauts de type III, comme les sursauts de type IV sont associés au type II mais avec quelques différences. Tout d'abord l'intensité spectrale est maximum au dessous de 100 MHz alors que l'intensité maximum du type IV se présente au ondes décimétriques. La durée est aussi plus faible, de l'ordre de $\frac{1}{2}$ à 3 minutes au lieu de plusieurs dizaines de minutes ou plusieurs heures. La température équivalente est 10 fois plus basse (10^{10} °K). La radiation est polarisée circulairement comme celle du sursaut de type IV. L'association entre type III et type V est apparemment mieux marquée qu'entre type II et type IV.

La source de la radiation paraît présenter les mêmes caractères. Il s'agit en fait d'une source ascendante, à une vitesse parfois grande (3 000 km/s), se stabilisant dans la couronne. Ainsi, il est possible que ces phénomènes soient déclenchés dans la couronne par un mécanisme de synchrotron.

Cependant la liaison physique entre type II et type IV, et entre type III et type V, reste mystérieuse. On pourrait imaginer que l'envol des particules (onde de choc dans un plasma à partir d'une région magnétique) apporte dans la couronne le champ magnétique nécessaire à l'émission de synchrotron. Il est possible également que la source ascendante responsable du continuum de type IV ou V soit aussi une source accélératrice fournissant l'envol et par suite les sursauts de type II ou III.

10. - Sursauts en U inversés, sursauts en arêtes, phénomène du 4 Novembre 1958.

Les spectres dynamiques montrent d'autres types de sursauts dont la cause est mystérieuse.

a) Les sursauts en U inversés (dans un diagramme fréquence-temps où la fréquence décroît en ordonnées) se présentent à peu près sous la forme d'un sursaut de type III mais l'extrémité supérieure en est recourbée et forme un crochet descendant. La durée totale du phénomène est de l'ordre de 30 s; l'intensité augmente avec la longueur d'onde; le phénomène occupe une large bande s'étendant sur le spectre métrique et décimétrique. La dérive de fréquence interprétée conventionnellement s'expliquerait par un mouvement ascendant, puis descendant de la source. Toutefois la vitesse de descente du même ordre que la vitesse ascensionnelle est énorme (50 000 km/s). Le phénomène paraît associé aux surrections chromosphériques (surges). Parfois des groupes de sursauts en U sont observés. Parfois le sursaut s'accompagne d'un continuum apparaissant après, aux fréquences basses du spectre dynamique.

b) Les spectres des sursauts de type II (cf. Section 6) sont parfois (10 % des cas) accompagnés de sursauts de type III en *arêtes*, c'est-à-dire situés de part et d'autre de la trace du type II (sursauts montants et descendants). S'il s'agit bien de types III simultanés au type II, il semble que l'envol de particules lentes dans la couronne doit être accompagné, sur le parcours de l'essaim, d'une émission sporadique ou récurrente de particules rapides vers le haut ou vers le bas. Observons que parfois les sursauts en arêtes sont seuls présents alors que la trace du type II est invisible. Parfois les sursauts en arêtes sont seulement montants, ou descendants. Parfois les deux harmoniques du type II sont pourvus de sursauts en arêtes.

c) Le phénomène du 4 Novembre 1958 correspond sans doute à l'émission radioélectrique solaire la plus mystérieuse et déconcertante par sa rareté, sa haute intensité, sa durée, sa variabilité considérable, et par les différences de détail observées sur des enregistrements à fréquence très voisine obtenus en des stations relativement peu distantes, alors que les caractères généraux de ces enregistrements coïncidaient parfaitement. Un tel phénomène a été observé une fois seulement, et exclusivement sur ondes *métriques*. En fait les observations sur 200 et 169 MHz de NERA, Nançay et Humain ont montré une énorme perturbation pendant plusieurs heures (08 h 40 à 15 h 15 TU) tandis que le flux enregistré sur 600 MHz à Humain et sur 3 cm à Nançay était parfaitement calme. La source du phénomène était située dans une région perturbée au sein d'une plage faculaire ancienne, et occupée à 09 h 37 par une éruption minime (importance 1); à cette source, de 8 à 10' de diamètre, se

superposaient de petites régions très brillantes et beaucoup plus étroites. L'émission n'a été accompagnée d'aucun sursaut de type III ou de type II, et la variabilité était très différente de celle d'un orage. Des variations très rapides observées à l'aide d'enregistreurs à grande vitesse la rapprochent plutôt d'une *scintillation*. Cependant les mesures effectuées sur 200 et 169 MHz en des stations distantes de 200 à 300 km donnèrent des enregistrements en corrélation pour les fluctuations relativement lentes, ce qui exclut la scintillation *ionosphérique*. Enfin, l'absence de corrélation pour les fluctuations rapides observées au même endroit sur 169 MHz avec une différence de 1 MHz seulement montre qu'il s'agit d'une émission dont le spectre est intrinsèquement très étroit. D'ailleurs cette circonstance est conforme à l'aspect du spectre dynamique obtenu à Ann Arbor. La cohérence, dans leurs grandes lignes, des mesures faites en des stations distantes, mais l'absence de corrélation dans le détails, font croire à une scintillation dans un milieu situé bien au delà de l'atmosphère, et peut-être dans la couronne solaire. L'origine de la radiation elle-même nous échappe actuellement [65].

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INTERVENTI E DISCUSSIONI

— M. MINNAERT:

Fait remarquer que, même à l'aide d'une antenne dont le pouvoir résolvant est insuffisant, il est possible d'obtenir des informations sur la distribution de brillance des sources relativement étroites.

— R. COUTREZ:

Fait observer que l'amélioration obtenue par le calcul est toujours limitée. En fait, les fréquences spatiales élevées, perdues du fait de l'extension finie des aériens, le sont définitivement sans qu'il soit possible de les restaurer. De plus, la solution théorique reste indéterminée par suite de l'extension finie du spectre de Fourier.

— M. MINNAERT:

Observe que les fluctuations du courant anodique des diodes possédant des cathodes

à oxyde sont nettement plus importantes que celles résultant de la formule de Schottky, en conséquence du fait qu'à la structure granulaire du faisceau électronique se superposent les émissions aléatoires de paquets d'électrons ou « scintillations ».

— R. COUTREZ:

Reconnaît la pertinence de cette remarque pour ce qui concerne la calibration des récepteurs radioastronomiques. Dans une calibration au moyen d'une diode de bruit, il est essentiel: *a)* d'éviter l'effet de scintillation des cathodes; *b)* de se placer dans les conditions de saturation. Ceci impose l'usage de cathodes métalliques pures. De plus la nécessité d'une distribution maxwellienne des vitesses électroniques conduit à choisir soigneusement la diode utilisée (diodes à électrodes planes, diodes coaxiales, etc.). De telles conditions font qu'il est difficile de considérer une diode de bruit comme un élément absolu. Les diodes coaxiales paraissent meilleures mais sont d'un prix assez élevé.

— M. MINNAERT:

Remarque que les antennes hélicoïdales peuvent, dans certain cas, recevoir d'autres composantes que la polarisation circulaire.

— R. COUTREZ:

Est d'accord, et fait observer que cela dépend avant tout de la structure géométrique de l'antenne à une longueur d'onde donnée. En fait, le diamètre, le pas, et le nombre de spires conditionnent la polarisation reçue. Lorsque ces éléments sont convenablement choisis, la polarisation circulaire est seule reçue; en même temps, le faisceau d'antenne devient exactement axial (« end-fire array »). Pour un nombre de spires trop faibles, ou bien si l'antenne fonctionne comme un réseau à rayonnement latéral (« broad-side array »), l'antenne hélicoïdale est sensible à d'autres polarisations, dont la rectiligne.

— M. MINNAERT:

Demande si l'argenture des lignes, guides, cavités, etc., ne permet pas de réduire les pertes ohmiques en accroissant la conductivité superficielle et voudrait comparer les mérites respectifs de cette argenture et du polissage optique du cuivre.

— R. COUTREZ:

Observe que l'argent se sulfure rapidement en l'absence d'une couche de rhodium; la conductivité s'abaisse rapidement par sulfuration, et même par rhodiage. Le polissage optique du cuivre, qui s'obtient par une technique très simple, donne des résultats excellents sans réduction appréciable de la conductivité superficielle par rapport à celle de l'argent métallique. De plus, la corrosion ultérieure étant fortement réduite par suite de l'adoucissement de toutes les irrégularités, les pièces ainsi traitées conservent leurs propriétés pendant plusieurs années.

A son avis, les résultats obtenus sont meilleurs que ceux fournis par argenture et rhodiage.

— M. MINNAERT:

Pose la question de savoir pour quelles raisons l'étalonnage des récepteurs ne s'effectue pas toujours au moyen d'une résistance chauffée, seul procédé absolu.

— R. COUTREZ:

Observe qu'il s'agit d'une question d'intervalle. Les résistances chauffées ne peuvent être portées qu'à des températures variant entre 0 et 1000 °K par exemple. Une diode de bruit permet d'atteindre des températures de bruit de 10000 °K à relativement basse impédance. Enfin, l'étalonnage thermique n'est absolu que si la résistance conserve la même valeur sur tout l'intervalle. Cependant, l'étalonnage des récepteurs aux hautes intensités requises en physique solaire dans le cas des sursauts pose encore certains problèmes.

— M. MINNAERT:

Observe qu'il existe un rapport étroit entre coefficient d'absorption et indice de réfraction. Dans ces conditions, le facteur de Gaunt qui figure dans l'expression du premier ne doit-il pas intervenir également dans le second?

— R. COUTREZ:

Observe que le lien entre indice de réfraction et coefficient d'absorption est une conséquence de la théorie de Lorentz, et plus généralement de l'équation de dispersion en théorie des ondes de plasma ou hydromagnétiques. Le facteur de Gaunt n'y intervient pas explicitement, et n'apparaît qu'en conséquence du principe de Kirchhoff à partir de l'émissivité calculée soit en théorie classique (Kramers), soit en théorie quantique (transitions free-free, bremsstrahlung, etc.). En comparant les deux expressions du coefficient linéaire d'absorption fournies: *a*) par l'équation de dispersion; *b*) par le principe de Kirchhoff, il devient possible d'établir une expression de la fréquence de collision électron-ion sans que l'indice soit affecté. Ceci limite la portée des résultats à l'équilibre thermodynamique local et n'est donc valable que pour l'émission thermique. En conséquence, une théorie plus développée semble possible et devrait être faite.

— M. MINNAERT:

Fait observer que l'introduction d'un facteur 4 dans les densités coronales obligerait à refaire tous les calculs des modèles solaires. L'idée de pouvoir se servir des mêmes résultats en changeant les fréquences dans un rapport convenable n'est pas applicable car le coefficient d'absorption dépend de N_e^2 tandis que l'indice de réfraction dépend en fait de $N_e^{1/2}$.

— C. DE JAGER:

Fait remarquer que les mesures de densités faites d'après les observations de l'éclipse de 1954 sont en bon accord avec la distribution de Baumbach-Allen-Van de Hulst pour la couronne.

— R. COUTREZ:

Est d'accord pour l'éclipse de 1954 qui a eu lieu au minimum solaire. Il fait remarquer cependant que les observations sur ondes métriques ne sont pas cohérentes. D'une part, la méthode des éclipses ne paraît pas fournir un pouvoir résolvant suffisant; d'autre part, les résultats interférométriques doivent être corrigés des effets instrumentaux.

— M. MINNAERT:

Pose la question des champs magnétiques coronaux et chromosphériques, qui peuvent intervenir à la fois dans l'indice et le coefficient d'absorption.

— R. COUTREZ:

Fait ressortir qu'en général, champ magnétique signifie activité solaire, mais qu'un champ magnétique coronal faible pourrait être pris en considération même pour le Soleil calme. L'expression complète de l'indice et du coefficient d'absorption résulte directement de la théorie de Lorentz si l'on tient compte du terme $\mu_0 e \mathbf{v} \times \mathbf{H}_0$. En présence d'un champ magnétique suffisant, la biréfringence s'installe et les niveaux critiques se séparent. L'altitude d'émission de l'onde extraordinaire est toujours supérieure à celle de l'onde ordinaire. On s'occupe actuellement, à l'ecle, d'extrapoler cette interprétation aux ondes électromagnétiques de plasma et hydromagnétiques, ce qui permettrait de dégager les théories de Piddington, Cowling, etc., des hypothèses de travail. Néanmoins, il paraît difficile actuellement de sortir de l'approximation linéaire.

— M. MINNAERT:

Fait remarquer la nécessité de faire des mesures du Soleil calme au moment du minimum *et* du maximum d'activité, les formes correspondantes pouvant différer.

Detection and Observation of Solar Emission in the Range of Centimetre-Waves.

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I.

The Techniques of Radio Radiation Measurements in the Range of Centimetre Waves.

1. – The boundaries of the frequency range chosen.

In the following lectures we are going to discuss measurements of solar radio radiation in the centimetre-wave range. More exactly, we shall discuss measurements in the range from 1500 MHz to about 100 000 MHz or in terms of wavelengths: from 20 cm to about 3 mm. At first sight the choice of this frequency range may seem somewhat arbitrary, but this range differs from that of the metre waves both with respect to the techniques of measurements and with respect to special problems of solar physics, so that a separate treatment seems justified.

The solar radiation in this frequency range is mainly generated in the chromosphere and its border regions. It is therefore the problem of this part of the solar atmosphere that we are going to discuss in some detail.

2. – Receivers.

In the majority of cases, present measurements of solar radiation in the centimetre range are concerned with determining the total radiation flux: but it is of equal interest to determine the brightness distribution over the disk of the sun or to determine the area of single phenomena with particularly

intensive emission. For all such measurements in the decimetre and centimetre ranges use is made of two types of receivers. They are the usual superheterodyne type of receiver and that of modulating type.

3. — Superheterodyne receivers.

The superheterodyne receiver used in radiometers of the cm-range are constructed in the usual way. According to cm-wave techniques the mixer is generally designed as a push-pull mixing unit in the form of the « magic T ». As a matter of course, the IF amplifier, particularly its first stage, as well as the mixer, must be constructed such that their noise is kept at a minimum.

In using such a receiver, it is important to know the limit of sensitivity attainable by it. Because of the noise generated by the receiver itself, the output meter shows fluctuations, the magnitude of which is given in terms of radiation temperature by writing

$$(1) \quad \Delta T = 1.5 \cdot F \cdot T_0 \cdot \sqrt{\frac{G}{B}},$$

where B means the bandwidth of the receiver at the input and G the bandwidth at the recorder. F is the noise figure of the receiver.

An example may serve to illustrate the situation prevailing in measurements of the total radiation. Let the receiver have a bandwidth of 6 MHz at the input and a bandwidth of 1 Hz at the output and a noise figure of 10. Then we obtain $\Delta\tau = 1^\circ.9$. If the dimensions of the aerial at 3.2 cm are chosen such that the sun fills only one-twentieth of the antenna beam, the noise to be expected at the aerial is about 800 degrees. Thus it is possible with quite a normal receiver to determine solar radiation with an exactitude better than one per cent.

Such a high sensitivity can be attained by normal receivers only for a short time or at great expense. What makes it so difficult is that the amplification factor of the receiver as well as the noise figure F are not constant. In measurements with highest sensitivity, variations of the amplification factor and the noise figure make themselves felt as a permanent irregular shifting of the zero point. Today this difficulty can be overcome, namely by arranging a proper circuit in such a way that the working point of each valve is kept constant. It is further necessary to use well stabilized power supply.

4. — Receiver of the modulating type.

In view of the disadvantages of the usual superheterodyne receivers another type of receiver is more and more coming into use in radio-astronomical meas-

urements. This type might be called receiver of the modulating type. It was DICKE [1] who first employed receivers of this type (Fig. 1).

In contrast to normal receivers, «modulating» receivers have a high-frequency switch in the aerial lead. The switch alternately connects the aerial and a noise source of known radiation to the input of the receiver. The switching

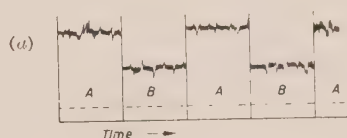
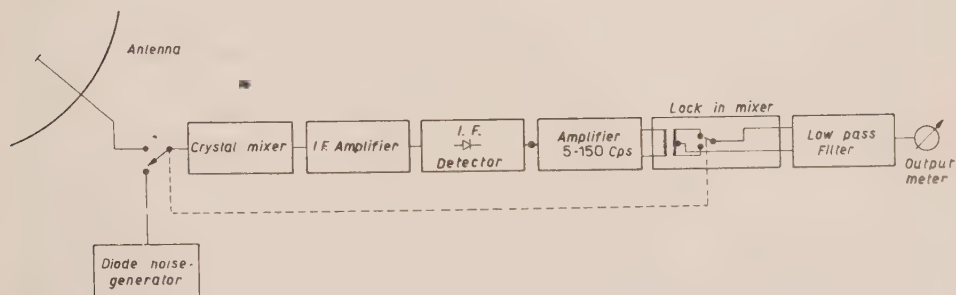


Fig. 1. — Receiver of modulating type [(a) signal at the output of the IF detector].

frequency is about 25 Hz. Thus the noise signal supplied by the aerial is modulated with the switching frequency in a meandering manner and made distinguishable from the receiver noise. Let us in this case consider the total signal at the output of the diode. Here the signal is composed of the receiver noise superposed by the amplified meandering signal from the input (see Fig. 1).

The rectifier is followed by a lock-in stage cutting the signal into the sections of the meander in such a way that the Sections A (the receiver noise plus the noise of the aerial or the signal) are obtained separately in one of two separate channels, while the Sections B (that is, the receiver noise plus the noise of the noise normal) are obtained in the other. If the currents in both channels are subtracted the receiver noise is reduced to a minute rest, and one obtains the difference of the signal minus the noise of the noise normal. If lastly the differential current is fed into a recorder through a low band pass, one obtains a very stable record that does no longer contain any variations of the receiver noise if the frequency of the latter is smaller than 25 Hz.

In comparison with a normal superheterodyne receiver the sensitivity of such a receiver is reduced by a factor of 0.4. The «modulation» receiver util-

izes only a fraction of the energy coming from the aerial. In this case we have

$$(2) \quad \Delta T = 3.7 \cdot F \cdot T_0 \cdot \sqrt{\frac{\bar{G}}{B}}.$$

But, as I said above, it excels by its greater stability.

5. - Compensation.

Another device that was suggested by MACHIN, RYLE and VONBERG [2] enables us to get rid also of amplification fluctuations by using a saturated diode as a noise source and adjusting its anode current in such a way that the noise of the normal is kept just as great as the signal. By subtraction in the lock-in mixer the signal is then just compensated. In this case the whole receiver acts as a zero instrument, and the anode current of the saturated diode is recorded. As a result fluctuations of receiver gain and receiver noise have only an indirect effect on the exactitude of measurements.

Despite the switch it is still necessary to construct the receiver in such a way that it generates minimum noise, for the noise figure F affects the sensitivity limit. Care must be taken for a sufficient stability of the power supply: in the same way outside disturbances have to be kept at a minimum.

In fact all these principles for the construction of receivers are known and have partly been dealt with in the preceding lectures. I am afraid I have been repeating familiar things. Let me therefore add some remarks that might be of interest. They concern the practical side of the operation of our receivers in the decimetre and centimetre ranges.

6. - Partial compensation.

We operate receivers at 1.25, 3.2, 10, 15 and 20 cm for daily measurements of solar radiation. All of our equipment has been constructed by the compensation method. But we have used Ryle's compensation method in a modified form. There are no satisfactory solutions for controllable diode noise sources in the centimetre range as there are for the decimetre and metre ranges. On the other hand, gas discharge tubes offer themselves as noise sources with a stable effect, but they cannot be controlled.

Fortunately solar radio radiation in the centimetre range varies very little within a period of twenty-four hours. This makes it possible for us to operate with fixed compensation. If at the beginning of a series of measurements the

noise generator is adjusted in such a way that its generated noise R is about equal to the radiation of the sun $S_{\odot}$, and if we take care always to keep

$$|R - S_{\odot}| < 1/10 S_{\odot},$$

then the fluctuations of the receiver are reduced by a factor > 10 . Thus it is easy to achieve that amplification fluctuations do not result in any changes of the records $> 1/100 S_{\odot}$.

If from time to time compensation is switched off for about 1 to 5 minutes, we obtain records with a calibration informing us on the amplification of the equipment. This kind of compensation has proved to be very useful.

7. - Switches.

One of the most important elements of a «modulating» receiver is, of course, the high-frequency switch. The switch should by no means add any noise to the receiver; it therefore has to act as a capacitive switch; on the other hand it should have high attenuation in the cut-off phase and low attenuation in the direction of passage.

Fig. 2 shows us how the problem has been solved for 20 cm waves [3]. The aerial lead and the lead from the diode noise source are joined in a point

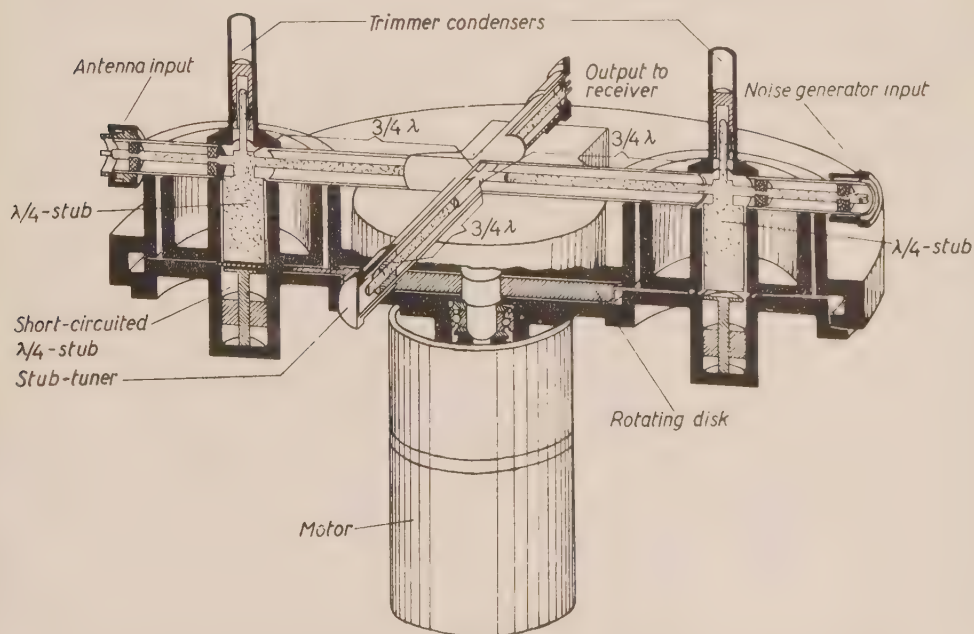


Fig. 2. - Cross-section of the rotating broad-band switch for 20 cm wavelength.

to which also the receiver input is connected. At a distance of $\lambda/4$ (or in this case $\frac{3}{4}\lambda$) from this branching point there is a tap line connected to the aerial lead and another one connected to the lead from the noise normally shortcircuited at $\lambda/2$. The $\lambda/2$ piece is interrupted in the middle, that is at $\lambda/4$, by a slit into which enters a rotating disk. The disk has a slot cut out in such a way that it alternatively shortcircuits the one branch lead at $\lambda/4$ capacitively, but at the same time sets free the opposite lead. The capacitive shortcircuit at $\lambda/4$ effected by the disk transforms itself as a resistance ∞ in the tapping-point so that at this point there exists a connection with the receiver, while on the other hand the $\lambda/2$ lead represents a shortcircuit in the tapping-point and thus effects an interruption in this lead.

In wave guide techniques such a switch looks a little different. In this instance it is convenient to use the attenuation disk suggested by DICKE. A disk, one half of which is lined with a resistor layer, enters into a slit of a wave guide. If the resistor layer dips into the wave guide the aerial lead is interrupted and at the same time the lead is terminated by a resistor at room temperature. In this case the signal coming from the aerial is compared with the thermal noise of the resistor. Of course, no compensation of the signal is possible in this simple form of the switch. In order to be able to use compensation also in the centimetre range, we have enlarged the switch to a double switch. The second part of the switch, consisting of a second rotating attenuation disk arranged at 180 degrees against the first, switches on the

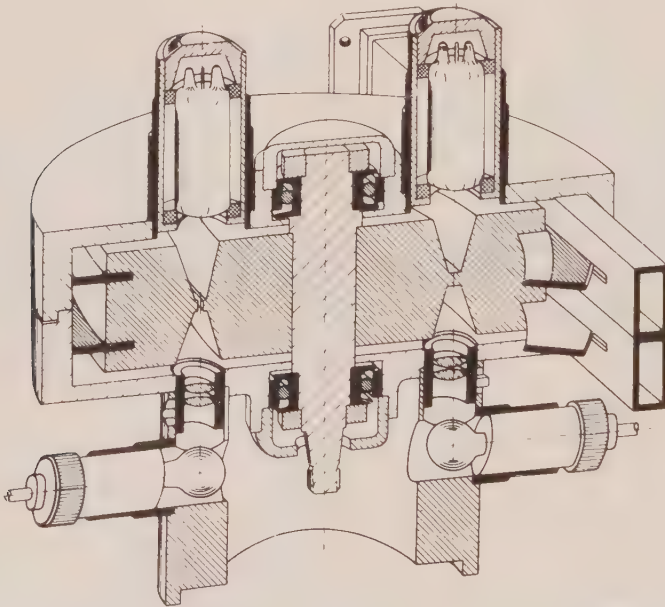


Fig. 3. — Cross-section of the rotating switch for 3.2 cm wavelength.

diode noise only if the aerial lead is blocked. The diode noise is coupled in into the aerial lead by means of a directional coupler. The construction of the switch can be seen in Fig. 3. The diagram shows the two wave guides with the attenuation disks and also the light sources and photocells by which the synchronization of the lock-in switch is controlled.

There has recently been a tendency to replace the mechanical switch by a ferrite switch. The principle of this switch is based on the Faraday effect for magnetized ferrite rods. If a ferrite rod is introduced into a cylindrical wave guide (H_{11} -mod-type) and magnetized longitudinally by an external magnetic field, an incident linearly polarized electromagnetic wave passing the ferrite rod is rotated in its polarization plane by a certain angle. The size of the rotation angle is proportional to the value of magnetization and thus to the strength of the external magnetic field.

If the external magnetic field is modulated with a certain amplitude and frequency, for instance such that in the one half of the cycle the field causes a rotation of just 45 degrees, and in its other half a rotation of 45 degrees in the opposite direction, then we practically have a switch. It is only necessary to arrange an absorbing strip after the ferrite rod in the wave guide. The wave passes this strip unattenuated if the electric vector is perpendicular to the absorbing plane; if however the electric vector lies in the absorbing plane, heavy attenuation takes place.

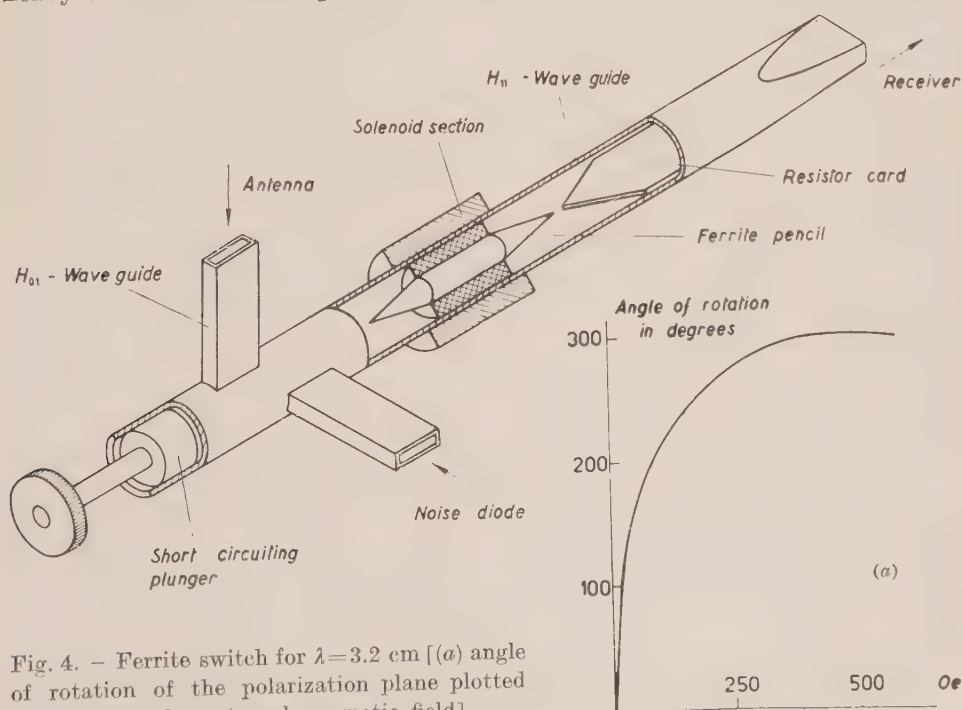


Fig. 4. - Ferrite switch for $\lambda = 3.2$ cm [(a) angle of rotation of the polarization plane plotted against the external magnetic field].

If it is desired to switch two signals alternately to one receiver in a similar manner as in the case of the rotating switch one has to choose an arrangement of wave guides bearing some resemblance to a circulator as shown in Fig. 4. The two wave guide couplers I and II form an angle of 90 degrees and are displaced by $\lambda/2$. This is on account of good coupling-out. The signals

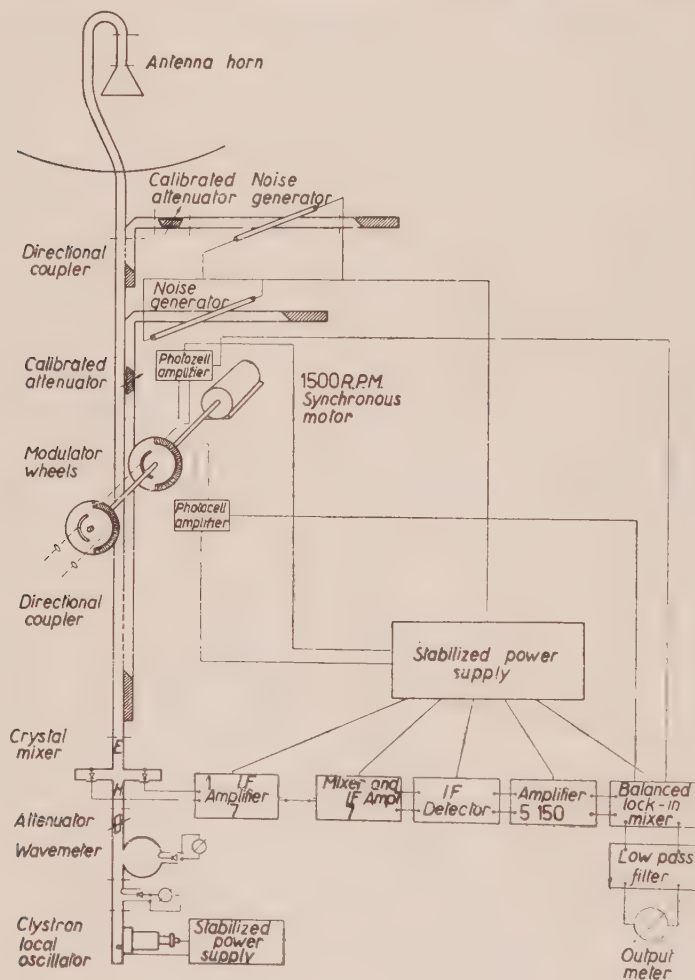


Fig. 5. - Block diagram of a 3.2 cm radiometer.

to be switched are coupled in through I and II. If the ferrite rod is not magnetized, signal II reaches the receiver while signal I is absorbed in the absorbing strip. In the period when the ferrite rod is magnetized and the rotation of the polarization plane is 90 degrees, signal I can reach the receiver while II is absorbed. Since the rotation of the plane of polarization is practically free from inertia it is possible to switch with higher frequencies (a few MHz).

The whole of the receiver is shown again in block diagram in Fig. 5. In this circuit arrangement compensation can only be used if the arriving signal is greater than $1 kT_0$, for in one of the positions of the switch the attenuation disk dips into the wave guide and generates noise of room temperature, whereas in the other position the antenna receives a radiation flux far below $1 kT_0$. In order to be able to measure very weak sources by means of the compensation method one has to introduce into the aerial lead an artificial noise of $1 kT$. For this purpose the second side branch has been inserted in the block diagram [4].

8. – Measurements of the total radiation flux of the sun.

For the purpose of daily observation of the sun «modulating» receivers have to be given preference, as we have seen. Another remark has still to be made with respect to the antennas. The main types of antennas used in the cm range are the horn and the parabola. The *optimum* size of the parabola is at $(30 \div 40)\lambda$. By choosing such dimensions for the aerial one obtains an antenna beam with a halfwidth of about 2 degrees. If the radiotelescope is directed towards the sun, a surface element at the solar limb is received with practically the same sensitivity as a corresponding element at the centre of the disk of the sun. As an example Fig. 6 shows the 1.25 cm radiometer, the reflector of which has a diameter of only 60 cm.

9. – Further development of radio receivers.

As regards the future development of radio receivers we are on the threshold of a period that will bring about considerable improvements, particularly in the decimetre and centimetre ranges. What will be the effects of such developments on solar research? Let us base our discussion of that question on the formula (1) for sensitivity given above.

1) The use of travelling wave tubes will make it possible to increase the input bandwidth B by a factor of 10 to 100; this will result in nearly tenfold sensitivity while the time resolution at the output remains the same.

2) By using molecular amplifiers of the maser-type the noise figure F of receivers can be reduced by a factor of 10 to 50; in this case, however, the amplifier allows only a narrow input bandwidth.

3) The same applies to the use of «parametrical amplifiers» which will equally permit to reduce the noise figure of a receiver by a factor of 10.

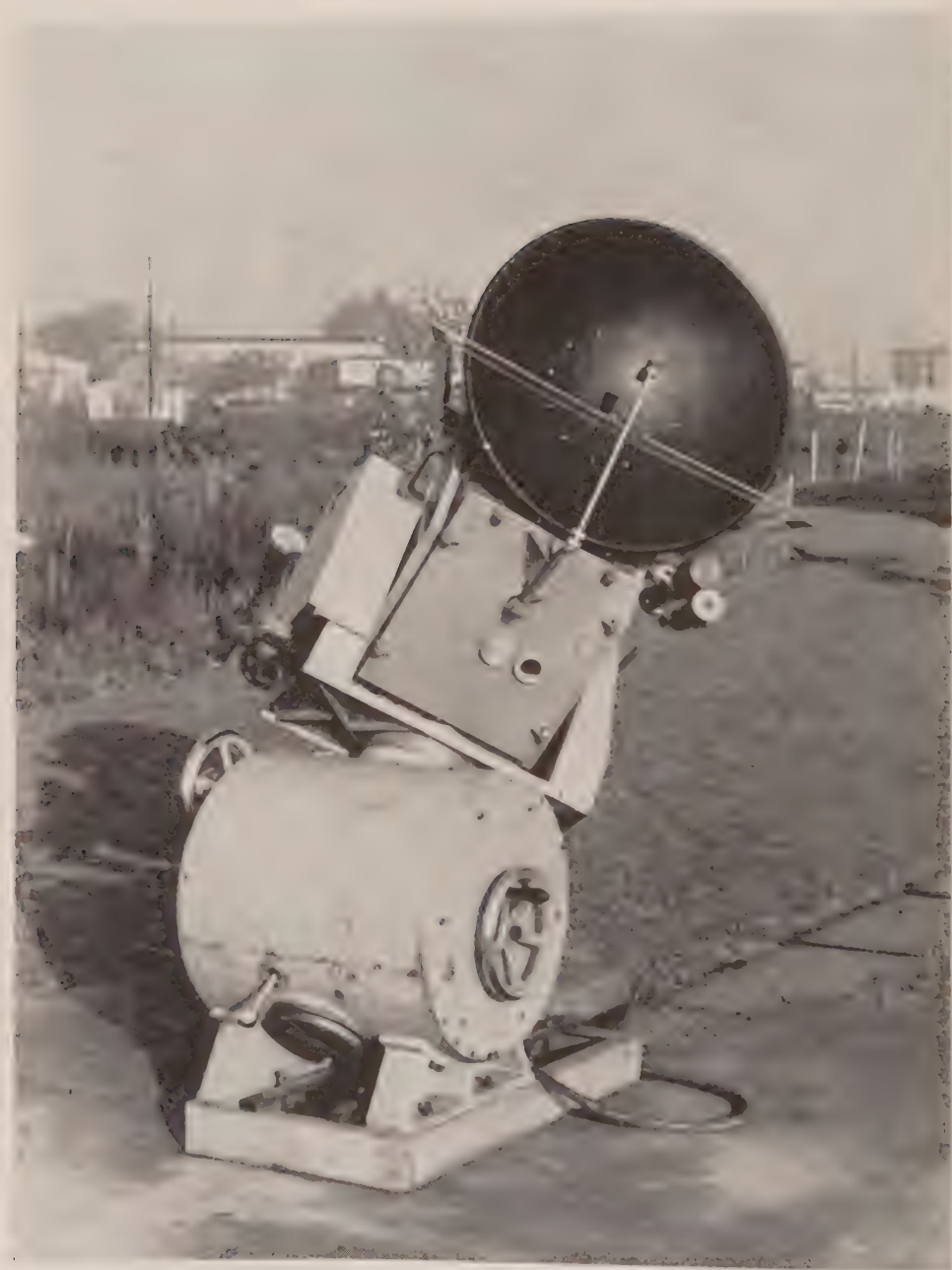


Fig. 6. - 1.25 cm radiometer.

4) If « parametrical amplifiers » and « maser » are arranged in the manner of travelling wave amplifiers they will make it possible to reduce the noise figure of the amplifier as well as to increase the input bandwidth.

The prospects for an increase in sensitivity are therefore promising, but in which way are we going to make use of them?

According to our present experience the spectrum of the sun in the range of centimetre waves is a continuum. For the time being there is no need to examine the radiation of the sun in very narrow ranges of the spectrum. Spectral lines will have to be expected only beyond the spectral range that we are concerned with.

It also seems that variations of radiation in time—even in the case of bursts—are not so short-lived that it would be worth-while to choose smaller time constants than $\frac{1}{2}$ s at the output of the receiver. In the near future there will be no need to reduce B or increase G .

It will be possible for us to use the gain produced by the new amplifier for increasing the sensitivity of the radiometers. An increase in sensitivity will prove useful at least in the case of burst records. For if the number of observed bursts is plotted versus their intensity (Fig. 7) their number rises considerably with falling intensity. That is to say, if sensitivity can be increased

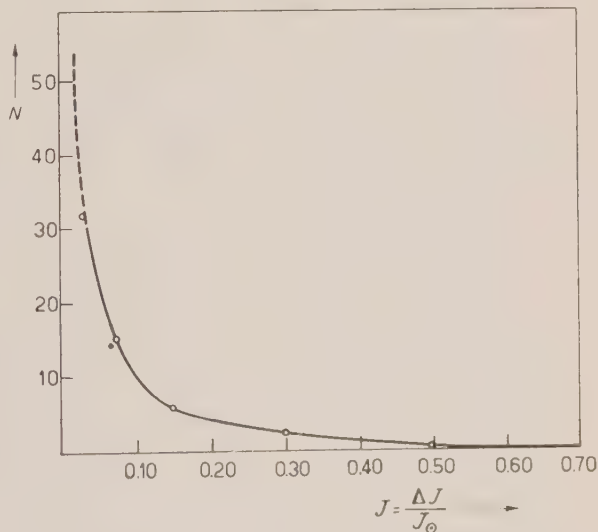


Fig. 7. — Number of bursts at $\lambda = 3.2$ cm versus max. intensity (N = number in intervals of $I = 0.01 I_0$).

we shall have to expect a considerably higher number of weak events. It can be concluded from the shape of the curves that if it will be possible to record with some certainty all events with maximum intensity greater than 1% of the total radiation of the sun, we shall then observe twice as many bursts as at the present time.

But then new obstacles will arise to a further increase in sensitivity in the centimetre range in the form of scintillation. Even now, in the case of zenith distances smaller than 60 degrees, we observe in our records occasional distur-

bance and unrest due to scintillation overshadowing many weak effects and making them unrecognizable.

An increase in sensitivity and the accompanying observation of a high number of very weak bursts gives rise to the question of the correlation of such effects with optically observed processes on the sun.

10. — The localization of areas of increased radiation on the disk of the sun.

The localization of areas of increased radiation on the sun—generally speaking, the determination of the intensity distribution over the disk of the sun—in the centimetre range by means of single aerials is still possible to a certain extent. The resolving power of an aerial at a given wavelength is proportional to its diameter measured in wavelengths. Or in other words the halfwidth of the antenna beam is

$$H^{\circ} = 60 \cdot \frac{\lambda}{D}.$$

An example will serve best to illustrate the possibilities contained in this formula. Let us take a parabolic reflector with a diameter of 12 m; its halfwidth at a wavelength of 1 cm is then

$$H^{\circ} = 0^{\circ}.05 = 3'.$$

The exactitude of the parabola however must meet the requirement that deviations from the ideal parabolic surface should not exceed ± 1 mm. Though this may seem a rigid demand, it can be satisfied for parabolic aerials up to a diameter of 20 m. In the case of 1 cm waves it would thus be possible to attain a resolution of about 1.8 by means of a parabolic reflector. It would be nearly a twentieth of the apparent diameter of the sun. Whereas in optical astronomy high requirements as to the quality of optical surfaces have been the rule already for a long time, it is only recently that we begin to cope with the same problem in radioastronomy.

At longer wavelengths the dimensions of parabolic reflector aerials increase very rapidly. In our radiotelescope at Berlin-Adlershof we have a strip of a length of 30 m and a width of 2 m built in for the purpose of tentative linear scanning of the sun with a resolution of 3'.5 (Fig. 8).

Above a wavelength of 3 cm the dimensions of radiotelescopes become so great that they make it unprofitable to construct equipment to obtain images of the sun in such a form.

For longer wavelengths we have the fine solution of the «crossed multiple



Fig. 8. 36 m radiotelescope of the Heisler-Hertz Institute (with inserted stripe of aluminum sheet for scanning the sun at 3.2 cm wavelength).

element interferometer » constructed for the first time at 20 cm by CHRISTIANSEN and co-workers [5].

CHRISTIANSEN, PAWSEY and MATHEWSON [6] were the first to succeed in recording images of the sun at a wavelength of 20 cm. It seems superfluous to discuss their procedure in detail since it has certainly become quite familiar.

11. — Determining the diameter of flare areas.

Another important method of measurement to be mentioned here is the determination of the diameter of burst areas in the centimetre range undertaken by KUNDU [7]. The emitting area of a burst is small; on the other hand its brightness is perhaps 100 times greater than that of the surroundings. The extent of such areas can be estimated by means of a two-element interferometer, and it is then possible to decide whether the emitting areas are considerably greater or smaller than the distance between two strips of the interference pattern projected onto the sky. For this purpose KUNDU chose a distance of 60 m (1860λ) for the two parabolic reflectors of 2 m of diameter; they worked at a wavelength of 3 cm. KUNDU was able to estimate the diameter within a range of about 1 to 3 minutes of arc. A confirmation of their measurements, if possible with a greater resolving power, would be desirable.

12. — Absolute measurements of radiation.

All measurements of solar radiation in the decimetre and centimetre ranges should lead to the absolute value of the radiation flux of the total disk of the sun or of a defined part of the surface of the sun. Absolute radiation intensities mark the beginning of any serious discussion either on the radiation of the « quiet sun » or on the radiation of the sunspot component or that of the bursts. Absolute measurement is equally necessary for a comparison of the radiation variation in different frequency ranges.

It must be said that in spite of the importance of absolute measurements investigations in this direction have rarely been made. The reason for it is, on the one hand, that the usual measurements have led to interesting results in many fields, which distracted attention from the painstaking absolute measurements. On the other hand such measurements are made difficult by several obstacles, so that absolute measurements in the radio-frequency range may justly be compared with the endeavours to determine absolute temperatures

in the optical range. For an exact treatment of absolute measurements the following secondary problems will have to be solved:

It will be necessary:

- 1) to provide an exact calibration standard for noise in the range between 1 and 5 kT ;
- 2) to carry out an exact determination of the aerial gain;
- 3) to treat in an exact manner attenuation and matching in the aerial lead;
- 4) lastly to measure the absorption by the terrestrial atmosphere and to know the amount of disturbing radiation from the surroundings of the aerial.

The variable temperature resistor has to be regarded as the most important calibration normal for absolute measurements in the frequency range under consideration. In Berlin we arranged different normal resistors and compared them with one another. We found that the normals, provided with different resistor layers, were all alike within $\pm 1\%$. The result is shown in the following Table I.

TABLE I.

Resistor substance	Temperature coefficient	X
Platinum sintered 1	$1 \cdot 10^{-3}$	3.23
Platinum evaporated	$1 \cdot 10^{-3}$	3.28
Boron carbide 1	$-1 \cdot 10^{-4}$	3.29
Boron carbide 2	$-1 \cdot 10^{-4}$	3.26
Platinum sintered 2	$+1 \cdot 10^{-3}$	3.30
Constantan wire	—	3.26

In the case of reflectors with a diameter of up to 4 m, as required for measurements of the sun, the aerial gain can be determined by direct comparison with calibrated aerals. But in order to avoid disturbances interspersed by the side lobes of the antenna beam, measurements should be made from two wooden constructions of about 20 m height and at a distance of 100 m.

Determining the attenuation in the aerial lead is a problem of measurement that can be solved in the laboratory. A simple reduction of errors of measurement is brought about by inserting a $\lambda/4$ piece of circuit and forming

the mean value between the first measured value and that read after inserting the $\lambda/4$ piece as it was shown by MOLLWO [8].

A determination of atmospheric attenuation was carried out by FÜRSTENBERG [9] at 20 and 3 cm. Since the attenuation varies slightly with time it would even be necessary to determine the daily attenuation value in an exact absolute measurement.

The problem of absolute radiation measurements in the centimetre-wave range can be solved; however, it will require painstaking efforts. But we shall find again and again that the discussion of measurements will convince us that we should not avoid to take that troublesome way.

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II.

Measurements of the Radiation of the Quiet Sun and of the Slowly Varying Component.

1. - The centimetre and decimetre wave radiation of the quiet sun.

We now turn to a discussion of the « quiet sun ». By the expression « quiet sun » we mean the state of the sun free from any centres of activity. We shall even go so far as to demand that no centres of activity should have been observed for at least four months. It is practically the state of the sun in a sunspot minimum.

The main object for measurements offered by the « quiet sun » is the radiation flux—or the brightness to be derived from it—which may be determined either as a function of the frequency or as a function of the place on the disk.

Directing our attention first to the dependence of the brightness on wavelengths we can only rely on measurements of a mean «effective value» for the total disk. The dependence of brightness on wavelength in a definite area at the centre of the disk would no doubt be an interesting question, but it has not been possible yet to answer it satisfactorily by means of direct measurements. The resolving power of the aerials at our disposal is still insufficient.

Since the radiation component of the «quiet sun» is of thermal character, it has become usual to state the measured brightness in terms of brightness temperature or effective temperature.

If the measured values of brightness temperature are plotted as a function of the frequency or wavelength (Fig. 9) it becomes obvious that the range of centimetre waves is a range of transition. The continuous spectrum of the range of millimetre waves is apparently a continuation of the optical spectrum. COATES and others [1-3] measured brightness temperatures between 4500 and 7000 degrees. Such temperatures have been determined in the optical region, too. But starting from about one centimetre, brightness temperature rises sharply and finally in the range of metre waves reaches values of more than 10^6 degrees [4]. For the reason of line emission of the corona in the optical region, it was possible to attribute these extremely high temperatures at a very early date to the plasma of the corona. I think we may take this for granted.

While on the one hand the brightness of the metre-wave radiation is determined by the temperature and density of the corona, and on the other hand the brightness in the millimetre range is given by the temperature of the photosphere, the centimetre and decimetre radiations depend on the state of

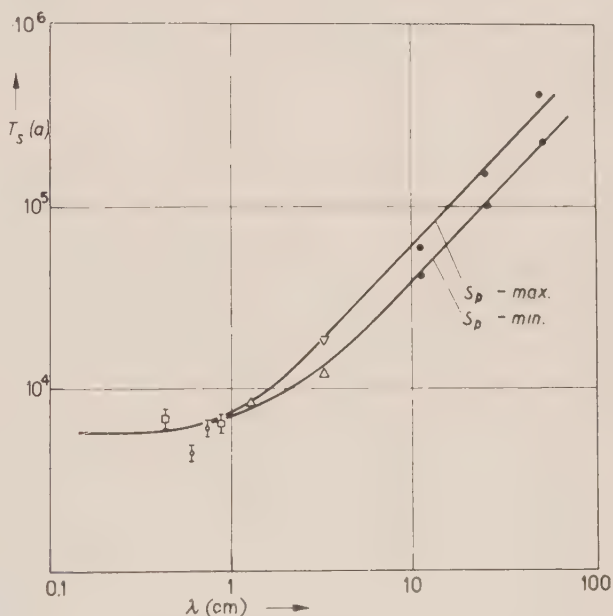


Fig. 9. — Radiospectrum of the sun for spot maximum and minimum at mm, cm and dm wavelengths. $\square$ 4.3 and 8.6 mm: [1]; $\circ$ 6 mm: [3]; $\bullet$ 7.5 mm: [2]; $\triangle$ 1.25 and 3.2 cm: [4]; ∇ 3.2 and 20 cm: Heinrich Hertz Institut, Berlin; $\bullet$ 10.7, 25 and 50 cm [5].

the intermediate region. The centimetre and decimetre radiations are essentially determined by the chromosphere and the two transitional regions between photosphere and chromosphere on the one hand and between chromosphere and corona on the other. Hence an interpretation of the rise in temperature in the centimetre range is very simple because of the dependence of optical thickness on frequency. With rising frequency first the corona, then the transitional region and lastly the chromosphere itself become optically thin.

Of course the portions of radiation contributed by the corona, the transitional region, and the chromosphere to the total brightness of a definite area of the solar disk do not only depend on the frequency, but also on the length of the path travelled by the ray in the respective region. The brightness, therefore, will not have at all points of the disk the same value as it has in its centre. We are thus led to the second question: the dependence of brightness on position over the disk of the sun. The dependence is characterized by the centre-limb variation. Measurements made during the latest sunspot minimum showed that the centre-limb variation is different in polar and in equatorial direction.

To get a complete picture it is therefore necessary to measure the brightness distribution over the total disk.

For a determination of the brightness distribution we require a measuring equipment with very high resolving power—or else we have to rely on measurements during solar eclipses. The only instrument suited for the direct determination of the brightness distribution in the range of decimetre waves is Christiansen's «crossed-multiple-element-interferometer». The interferometer has a resolving power of $3'$, that is one-tenth of the diameter of the sun.

Equally suited is strip integration of brightness by means of linear multiple-element-interferometers, if it is possible to carry out measurements in different directions relative to the axis of the sun. Interferometers of this kind are built at Ottawa for 10 cm with a resolving power of $1'$ by Covington, and at Tokyo, Pulkowo and Paris. From such measurements it is then possible to derive the brightness distribution over the disk of the sun by a two-dimensional Fourier transformation. The evaluation of the results is made difficult by several problems of aerial smoothing. The present maximum resolution attained by interferometer measurements is between 2 and 3 minutes of arc. The resolving power is still relatively small for measurements of the brightness variation at the extreme limb of the sun. Measurements of solar eclipses have still to be preferred for such special problems.

Contrary to the limb darkening in the range of metre-waves we can observe limb brightening in the range of centimetre-waves and in the lower part of the decimetre range. Isophotic diagrams of the brightness distribution measured in the latest sunspot minimum are given in Fig. 10. The pictures show the

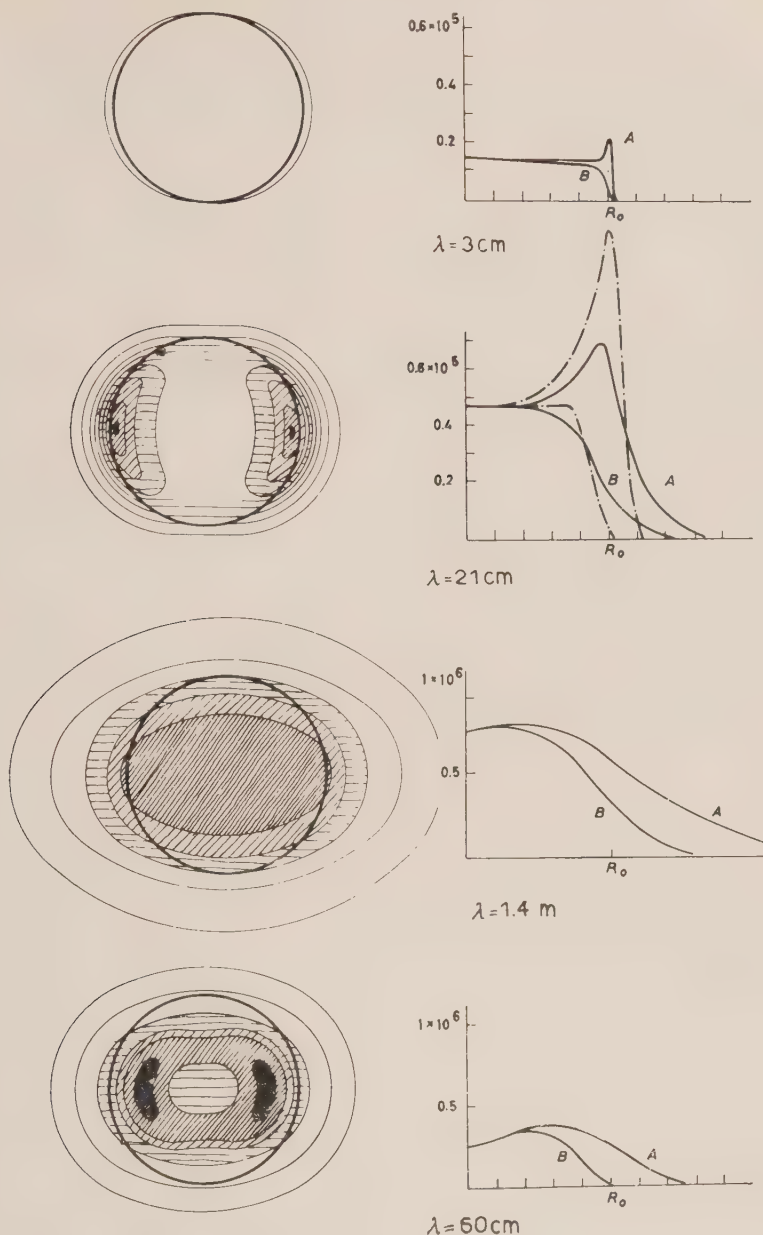


Fig. 10. Average radio brightness distribution over the quiet sun. Curves A: along the equator. Curves B: in polar direction. References: 3.2 cm: J. ALON, J. ARSAC and J. L. STEINBERG: *Compt. Rend.*, **237**, 300 (1953); 20 cm: W. N. CHRISTIANSEN and J. A. WARBURTON: *Austral. Journ. Phys.*, **8**, 484 (1955) and O. HACHENBERG, F. FÜRSTENBERG and H. PRINZLER: *Zeits. Astrophys.*, **39**, 232 (1956); 60 cm: P. A. O'BRIEN and E. TANDBERG-HANSEN: *Observatory*, **75**, 13 (1955); 140 cm: A. HEWISII: *I.A.U. Symposium*, no. 4, 300 (1957).

degree of symmetry of the brightness distribution of the «quiet sun». Limb brightening is confirmed beyond any doubt. But if we compare the distributions derived at a given frequency, the measurements still turn out to be widely different.

The task of a theoretical discussion of these measurements—in the same way as in the metre range—consists in determining density and temperature of the emitting layers. This seems somewhat easier than in the case of the metre range, for the propagation of centimetre- and decimetre-waves in the regions of the solar atmosphere under consideration is for the most part linear. The refraction of the rays may be neglected. Still the calculation of density and temperature distribution from the brightness distribution is very complicated. It is therefore more convenient to start from a «model corona» or a «model chromosphere», the parameters of which are taken from optical observations or from general requirements of balance. The brightness distributions derived from such models are next compared with measurements.

In the case of decimetre-waves, the thickness of the coronal layer may be regarded as great in comparison with that of the chromosphere, since a large portion of the radiation comes from the corona. One need not use a more detailed model of the transitional layer and the chromosphere. It is sufficient simply to characterize the chromospheric portion of the radiation by a mean brightness temperature.

In the centimetre range things are different. Here the origin of the radiation is almost exclusively in the chromosphere. The model must allow for typical characteristics of the chromosphere, as for instance spiculae. Conversely the most important radio-astronomical data, needed for the completion of the chromospheric model as obtained from optical information, may be expected to come from observations at centimetre-wavelengths.

Without entering into any details it is possible

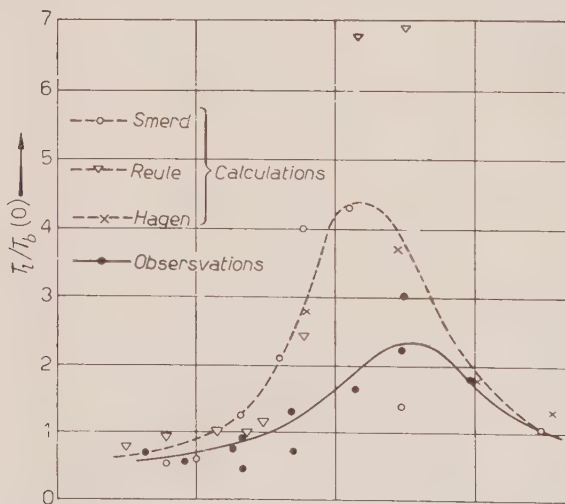


Fig. 11. — Comparison of observed and computed parameters of the solar brightness distribution (T_l being brightness temperature of the brightness maximum at the limb, $T_b(0)$ brightness temperature of the centre of the disk). (After C. DE JAGER: *Handb. d. Phys.*, 52, 295 (1959)).

to get an idea of the present relation between measurements and calculations by examining the relative limb brightening (that is: the brightness at the maximum of the limb brightening/brightness in the centre of the sun) as a function of frequency. It turns out then that the calculated values for this relation in the decimetre range are two or three times larger than the measured values (Fig. 11). In this case however the calculation was based on a simple model, that is to say a spherical, isothermic, and homogeneous model.

Best founded among the suppositions made in these models seems the use of a constant mean temperature instead of the existing spatial temperature distribution. For even from the conditions of the hydrostatic balance follows a relatively small variation of the coronal temperature.

It is more difficult to answer the question whether it is justifiable to neglect the scatter at the inhomogeneities of the corona that are to be found in optical photographs. It is just such a scatter which seems suitable for flattening the steep curve of the calculated limb brightening, so that a better agreement with the measured curves would be brought about. Studies in the range of metre waves dealing with limb darkening as well as with the occultation of radio sources (HEWISH [6], SCHEFFLER [7], VITKEVITCH [8]) in fact have shown that this scatter should not be neglected. On the other hand it might be expected according to the theory of this forward scattering that its influence would become considerably smaller with decreasing wavelength.

It therefore seemed more appropriate to include in the calculation the more easily seizable influence exerted by deviation from spherical symmetry. Corresponding calculations were carried out by WALLIS [9]. WALLIS based his calculations on a rotational-symmetrical model of the corona, as it was derived by WALDMEIER according to the brightness distribution of the photospheric light scattered in the corona. The resulting integrals only have to be calculated numerically. The method used was the following: WALLIS compared the measured and the calculated strip integrals directly, for a direct comparison is easier and leads to more exact results. Thus he could avoid the uncertainty which arises if the brightness distribution is derived from measurements by means of two-dimensional Fourier transformations. It could be shown that discrepancies between measurements and calculations may be essentially reduced by means of a rotational-symmetrical model. The radiation contributed by the chromosphere was taken into account by means of a mean brightness temperature.

On the other hand we may expect some further changes from new measurements. Some progress has been made as regards the precision of interferometer measurements, the planned observations of the next solar eclipse and lastly, the methods of aerial smoothing. We may expect important data from observations to be made during the next sunspot minimum.

2. - The slowly varying component of solar radio radiation.

Introduction. - The slowly varying component of the radio frequency radiation of the sun was first discovered in 1946 by HEY [10]. Since that time it has become the subject of numerous studies.

This component is superposed on the radiation of the quiet sun and is very strongly marked in the range between $\lambda=1$ cm and $\lambda=60$ cm. As is

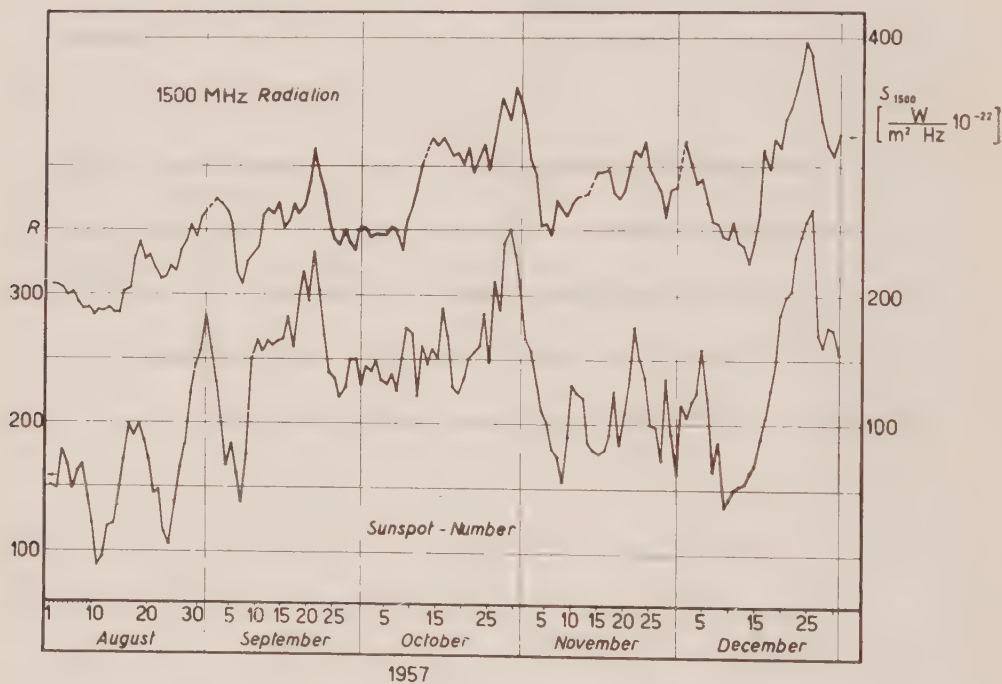


Fig. 12. - Observed variation over several months of solar radiation at a frequency of 1500 MHz together with sunspot numbers.

generally known, its intensity varies little from day to day and is closely correlated with sunspot-activity. This variation is one of the reasons for the great importance of daily observations of the sun as they are practiced nowadays by many observatories. Examples of such measurements are shown in Fig. 12, where the daily mean value of the 1500 MHz radiation recorded at Berlin-Adlershof, are compared with the Zürich sunspot numbers at the time of the maximum of the present sunspot cycle.

2'1. Statistical investigations. - In case solar eclipse observations or interferometer measurements are not available—for solar eclipses are rare and up

to now interferometers are only available at very few observatories—we are left to derive our information about this component from the daily measurements of radiation. These radiation measurements refer to the total sun; the measured values are an expression of the interaction of several single phenomena, for the discussion of which statistical methods have to be used. This has been done by a number of workers.

In this way for instance already in 1949 DENISSE [11] and PAWSEY and JABSLEY [12], using statistical methods, proved the existence of two components in the solar radiation of decimetre-wavelengths, one of which was constant over long periods, while the other showed a high correlation with the sunspot area. Both authors already supposed a thermal mechanism of emission for the two components. Further statistical work was undertaken by PIDDINGTON and DAVIES [13], COVINGTON and MEDD [14], TANDBERG-HANSEN [15], ALLEN [5], and others. As a measure of solar activity was taken the sunspot area A or the relative sunspot number R . At first it seemed

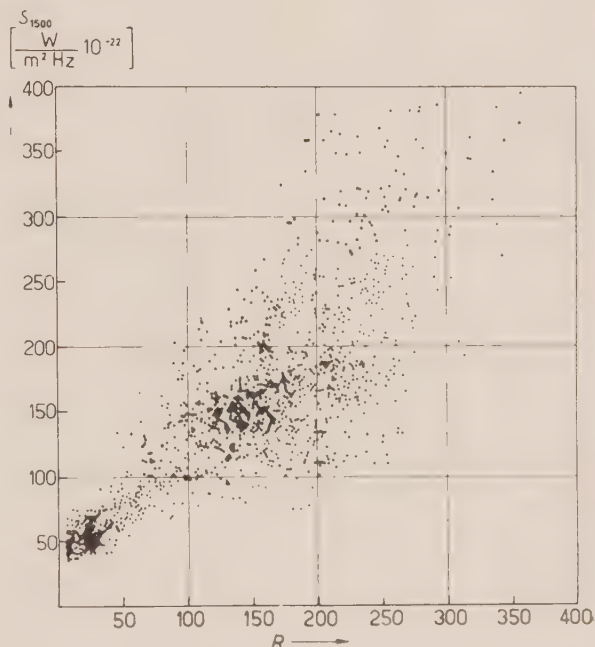


Fig. 13. — Correlation diagram between observed solar radiation flux at a frequency of 1500 MHz and sunspot numbers R for the time from 1954 to 1958.

also promising to use the plage area F as well as the magnetic fields of sunspots, but no essential improvement of the correlation was brought about by this. On the other hand some statistics indicated an after effect of past spot areas in the radio frequency range.

By plotting the flux density S at a definite frequency versus one of the above data A , R or F , one obtains a scatter of points with a regression linear in first approximation. Such an example is shown in Fig. 13. Here the daily mean values of the 1500 MHz records by the Heinrich-Hertz-Institute are plotted versus the Zürich relative sunspot numbers for the period August 1954 to December 1957. The correlation coefficients between these two values for

the first and second six months of 1956, for instance, are 0.71 and 0.75, and for those of 1957, 0.81 and 0.76 respectively. At $\lambda = 10$ cm the correlations seem to be even higher, with a maximum at $r = 0.85$. The gradient of regression and the extrapolated value of the radiation of the spot-free sun rise with increasing spot numbers. Fig. 14 shows the correlation for a section of the sunspot minimum and a section at the time of the maximum. The periods chosen are the second half of 1954 and of 1955, and the first half of 1957. (*)

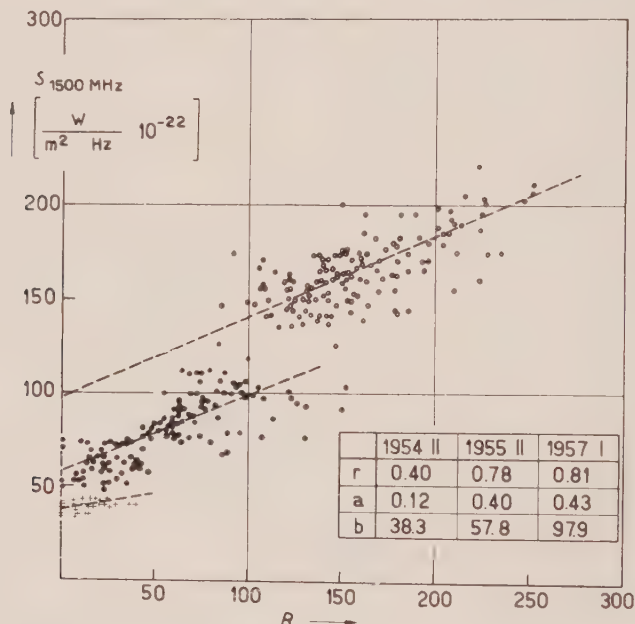


Fig. 14. — Correlation diagram between observed solar radiation flux at a frequency of 1500 MHz and sunspot numbers R (+ +) for 1954 II, (● ●) for 1955 II and (○ ○) for 1957 I.

In this we see at least partly an expression for the fact that the spot-free sun shows a slow variation of electron density and electron temperature in the lower corona in the rhythm of the eleven-year sunspot cycle.

It should be mentioned, however, that PIDDINGTON and DAVIES [13] tried to explain this increase in flux density of the spot-free sun during the spot maximum as an after-effect of the centres of activity, which may still be effective after more than 3 rotations of the sun.

The present statistical material makes it difficult to decide which of the two above views should be preferred. ALLEN [5], who made such an attempt,

(*) The results have been taken from an unpublished study by KRÜGER and WALLIS.

found that an eleven-year period of the radiation of the quiet sun would have to be supposed in the decimetre range as well.

In other respects the radio frequency radiation in the decimetre range is in good accordance with the relative sunspot number, so that it is suggested to replace the relative sunspot numbers, which are fixed empirically and are not subject to exact physical definition, by the very reliable daily values of radiation as a measure of solar activity. The values of Ottawa at $\lambda = 10.7$ cm, which are available over an uninterrupted period since 1947, might be used instead. This observational series has already proved useful for comparisons with ionospheric data in particular [6].

2.2. Coronal condensation models. — For a better understanding of the slowly varying component, different models as to the regions of origin of this radiation have been suggested by DENISSE [17], PIDDINGTON and MINNETT [18], and WALDMEIER and MÜLLER [19]. DENISSE supposed that magnetic fields of sunspots lift the emitting regions from the colder chromosphere up to the hotter corona [17]. In this case a percentage of circularly polarized radiation would have to be expected.

In better accordance with measurements, and perhaps generally accepted today, is the idea suggested by WALDMEIER and MÜLLER, that the sunspot component has its origin in the hotter and denser parts of the corona, the so-called coronal condensations. The slowly varying component is thus interpreted as being thermal. In a way the suggestions by PIDDINGTON and MINNETT are a combination of the two above mechanisms.

So the models start from the idea that a gas volume with enhanced electron density extends from the upper boundary of the chromosphere up into the corona. Let us consider the emission of such a gas volume. Supposing thermal emission, we can describe the brightness by taking

$$J_{\nu}(T) = B_{\nu}(T) \cdot (1 - \exp[-\tau_{\nu}]) ,$$

where $B_{\nu}(T)$ means Planck's law and τ_{ν} the optical thickness. At low frequencies, where $\tau_{\nu} \gg 1$, the volume emits a black body radiation. At higher frequencies τ_{ν} becomes less than 1, and eventually the volume of gas emits a spectrum of equal energy.

WALDMEIER in his model composes the coronal condensation of four ranges of different electron density, but equal temperature, enclosing one another in a shell-like manner. Calculating the flux density of this model and expressing this radiation by the apparent disk temperature relative to the spot-free sun we obtain curves depending on the wavelengths as shown in Fig. 15.

Fig. 15 contains the theoretical curves of Waldmeier's model for two different electron temperatures. The figure also contains a theoretical curve of

Piddington and Minnett's model. Finally it shows measurements for two single days and a mean curve of the dependence on frequency of the sunspot component taken for six months.

We can see a qualitative accordance with Waldmeier's models. Of course different temperature and density distributions in the centre of emission would result in a group of such curves, filling a whole range (shaded in Fig. 15).

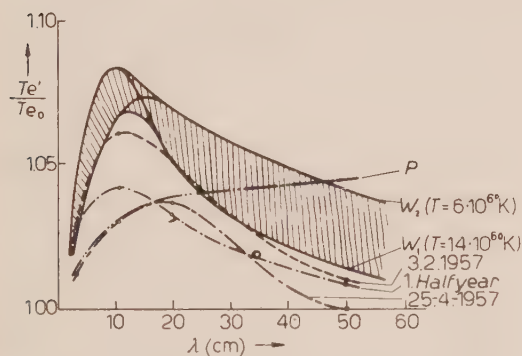


Fig. 15. — Comparison of observed and computed brightness distributions of the slowly varying component. Observations: Heinrich Hertz Institute, Berlin (3.2 and 20 cm); Ottawa (10.7 cm); Prague (50 cm). Calculations: $W_1 W_2$, Waldmeier-Müller-model; P Piddington-Minnett-model.

lap and are expressed in the measured values. Starting from such considerations it is necessary to undertake a critical examination of statistics.

2'3. Interferometer and eclipse observations. — More detailed statements about individual radiation centres are made possible by interferometer measurements or by observations of solar eclipses. The latter supplied the first proof that the slowly varying component is emitted by discrete areas on the surface of the sun coinciding with the sunspot areas. But only interferometer measurements made it possible to carry out systematic observations of single centres of emission. Their development, the limb darkening and other points of interest thus can be studied. In particular, new progress in the research of the slowly varying component has been made by observations carried out in Sydney since June 1957 with the high-resolving « crossed-multiple-interferometer » at a wavelength of 20 cm.

2'4. A summary of our present-day knowledge on the nature of the sunspot component. — The emitting areas lie above the optically visible centres of activity and as to form and size they are very similar to the (Ca) plage areas. Their

Applying this to our scatter of points (Fig. 13) we find that the points need not be situated on a straight line. Because of differences in temperature and density in the single condensation, the values scatter over a broad range bordered by two straight lines. The angle of aperture of the lines depends on the range of scattering of the flux density of the possible models. The conditions are further modified by a variation of the basic level in the course of a sunspot cycle as well as by the after-effect of past spots. All these influences overlap

extent is of the order of 5 minutes of arc, which corresponds to 250 000 km on the sun. The altitude of the centres of emission can be calculated from their different apparent velocity as compared with plages or spots of the photosphere in crossing the solar disk because of the rotation of the sun. The resulting altitude varies from 20 000 to 100 000 km the average given being 50 000 km.

The brightness distribution over the solar disk of the slowly varying component obeys very exactly a cosine law, except in the limb region [20]. This indicates a small extent in altitude of the regions of emission as compared with their horizontal dimension. An east-west asymmetry of the centre-limb variation was not found. Accordingly, the coronal condensations would have the form of flat disks arranged parallel to the photosphere.

The radiation temperatures of the regions of emission are on the average of an order of $0.6 \cdot 10^6$ °K. They reach from low temperatures up to a limit of $1.5 \cdot 10^6$ °K corresponding to the temperature of the corona. It must be noted in this respect that errors in estimating the size of radio sources may result in radiation values that are either too high or too low. The fact of the cutting-off of these temperatures at the temperature of the corona is an indication that the sources of the radiation have to be regarded simply as condensations in the corona.

The life-time of the regions emitting the slowly varying component is above three months, and is longer than that of corresponding groups of spots. As however, in the maximum phase there is a high correlation between the spot-area and the flux density of radio frequency radiation, the differences between the optical phenomena and the radio frequency radiation in later stages of development are not strongly marked in statistics. Systematic variations in size and altitude have not yet been found.

With regard to the spectrum of the slowly varying component, the curve shown in Fig. 15 is valid along general lines. More detailed examinations particularly as to the differences in the spectra of single regions of emissions on a larger scale are still lacking.

In Fig. 16 the daily mean values of flux density measured at different times are plotted for some frequencies in the centimetre and decimetre ranges. A comparison of the two diagrams reveals characteristic differences in the spectra that need further investigation. In this respect it is important to solve the problem of absolute calibration of the receivers for as many frequencies as possible and over long periods.

It is worth mentioning that also the slowly varying component of the ultra-violet and X-radiation of the sun—in the same way as bursts—is very similar to the radiation in the centimetre and decimetre ranges. It is possible that both radiations originate from the same place on the sun.

Concerning the polarization of the decimetre radiation, it may be mentioned that no polarized part has been found at $\lambda = 20$ cm [21]. Small

amounts of circularly polarized radiation were observed at $\lambda = 10$ cm and $\lambda = 3$ cm [22]. This result is not in favour of a magnetic-ionic explanation of the slowly varying component, though it is possible to indicate mechanisms

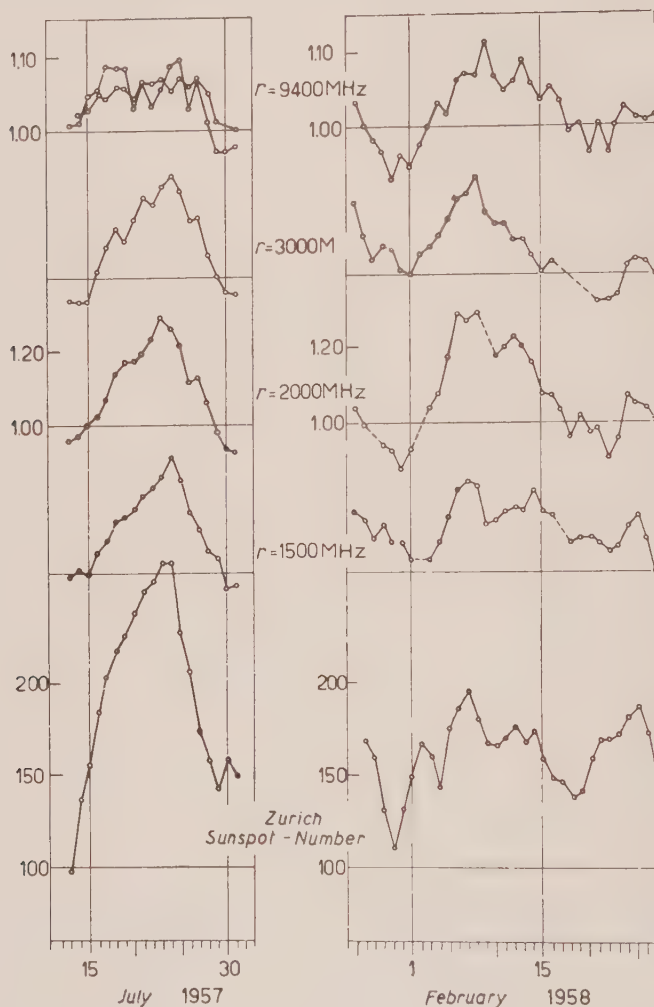


Fig. 16. — Observed variation of solar radiation at different frequencies during two selected time intervals.

according to which polarization need not be found in the measured radiation. Moreover, no connections have been found between the magnetic field of the spots and the temperature and altitude of the sources of radiation. A connection between plages, local magnetic fields, and radio sources found by

BABCOCK [22] rather points to a role of the magnetic field in forming regions of high electron density.

Further advances in our knowledge on the nature of the component may be expected if interferometer observations will be made for different wavelengths in the centimetre and decimetre ranges at the same time.

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III.

Burst Radiation in the Centimetre Waves Range. Variation and Spectrum.

1. — Classification.

The variation with time of burst radiation in the centimetre waves range—to put it briefly: the form of the bursts—is obviously different from the known variation in the metre range. The records of the centimetre range do

not show the numerous and sharp peaks that are typical of the metre range; they are rather smooth.

In order to classify burst forms COVINGTON [1] some years ago set up a series of types; an improved version of this classification was used for the characterization of bursts in the International Geophysical Year. Covington's types cover the following phenomena: typical peaks of $\frac{1}{2}$ to 5 minutes duration; peaks with a postburst increase of the radiation level; bursts with a «gradual rise and fall» of intensity; composite types and big outbursts of radiation. Covington's types are a convenient means of a short-hand characterization of burst forms.

But it seems that at least between some of the types there exists no major difference that would be based on the physics of the events.

2. — Typical features of burst records.

We are not going to discuss here COVINGTON's well known series of types. Instead, let us try to derive some typical features from the shape of burst records [2, 3]. A number of burst records is shown in Fig. 17. A survey of

these records directs our attention to the following typical characteristics.

Certainly the most important element in burst records is the single peak. A single peak is characterized by a mostly very steep rise and a somewhat less steep fall. In order to characterize it we shall use the half width or the width at 75% of its maximum intensity. If we consider the frequency of the so determined width of these peaks, we get the following picture (Fig. 18): the peaks have an average width of circa 30 s duration. Very short peaks below 10 s are practically non-existent. Towards long durations the peak will apparently change to a type similar to that of «gradual rise and fall». The form of these peaks is sure to be of extraordinary importance for the subsequent discussion of the excitation process.

A further characteristic of burst re-

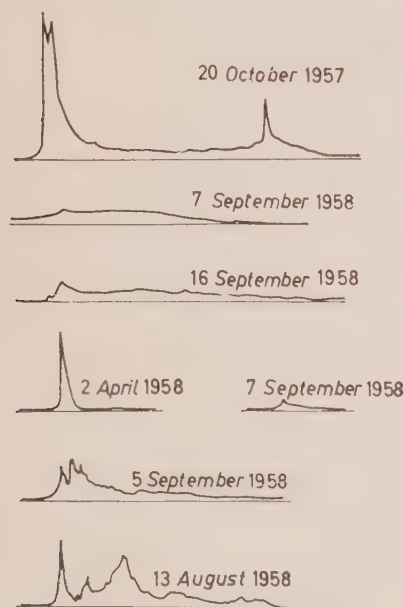


Fig. 17. — Records of different bursts at 3.2 cm wavelength.

cords is the «postburst increase», an increase in brightness often occurring immediately after a peak or a group of peaks. It seems that occasionally

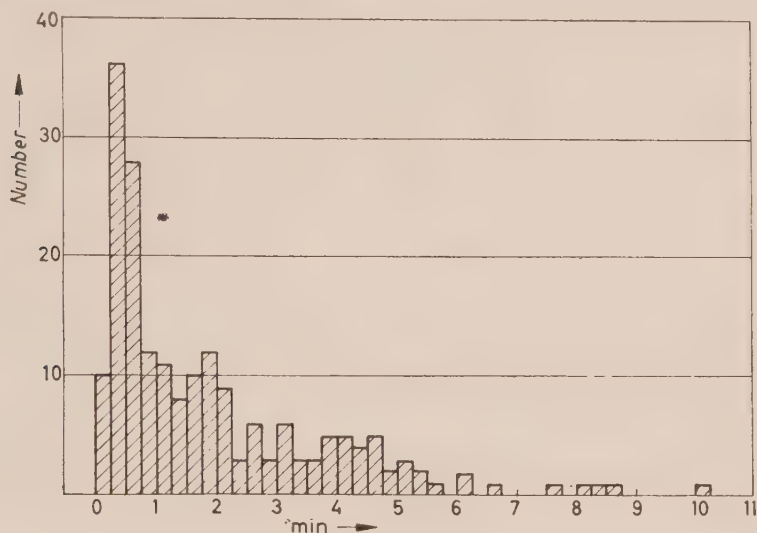


Fig. 18. — Distribution of the $0.7 J_{\max}$ widths of burst-maxima at 3.2 cm wavelength.

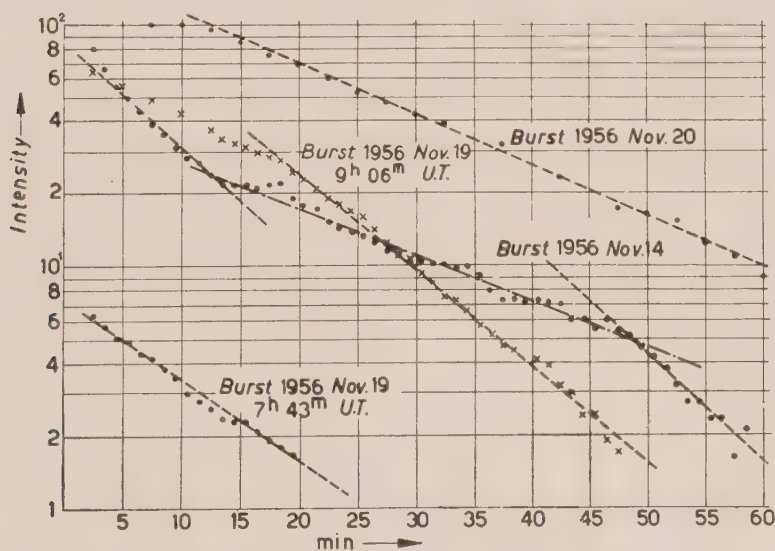


Fig. 19. — Decay of the radiation at the end of four outbursts.

this increase in brightness may also be composed of single excitation pulses of several minutes duration, which, taken as a whole, produce an increase in radiation with an undulating upper edge. Very probably there is a con-

tinuous transition to the very slow «gradual rise and fall» type of burst, which therefore need not be mentioned as a characteristic feature. The underlying physical process seems to be similar in both cases.

A third characteristic, to be found particularly towards the end of heavy bursts, is a monotonic decay, which in many cases closely resembles an exponential decay. The decay occurs with a time constant of about 10 to 40 minutes; but a duration of circa 13 minutes seems to prevail. The long times of decay seem to be caused by further weak excitation pulses. Fig. 19 contains the decay of four major bursts in a logarithmic scale.

3. - The shape of bursts at different frequencies in the range of centimetre waves.

If we compare records of a burst that were made at different frequencies in the frequency range in question, we shall find that the curves—contrary to their behaviour in the metre range—display a striking similarity. The single

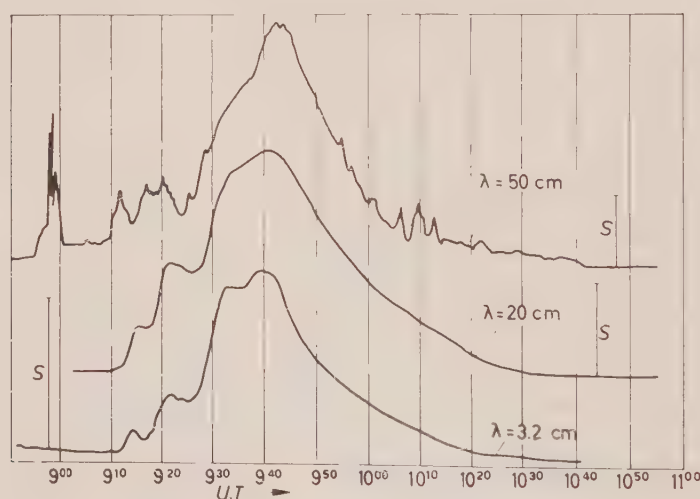


Fig. 20. - Records of the burst of 1956 Nov. 19 9^h 07^m U.T. (*S* denotes solar radiation of the day of observation).

maxima of peaks can be observed at widely different frequencies. Not rarely the records obtained at a wavelength of 20 cm are nearly the same as those obtained at 3.2 cm. Fig. 20 shows a typical example of this kind. While the curves recorded at 3, 10, 15 and 20 cm respectively are very similar, the records obtained at 50 cm change to a different type.

In other cases the similarity of the records is not quite obvious. Yet the

similarity becomes clear if the times of occurrence of the maxima in the records are compared with one another. Then it turns out that the maxima occur at nearly the same times, but the intensity of radiation in the different maxima seems to be subject to noticeable changes.

If the intensity of the maxima is given relatively to the daily value of the solar radiation at the respective frequency, we can find many cases in which this relative intensity of the maxima increases with decreasing frequency. Such a case is illustrated in Fig. 20. Concerning the increase in relative intensity of a burst maximum toward longer wavelengths, it is not surprising that some maxima are very easily detectable at a wavelength of 20 cm, whereas at 3 cm they have fallen below the limit of detection.

Beside the monotonic rise of relative intensity towards lower frequencies there are at least as many instances in which the intensity of a burst has a flat maximum in the middle of the frequency range and declines slightly towards the two boundaries of the range (Fig. 21).

Lastly we had observed maxima having a highest value at 3 cm, their relative intensity decreasing with decreasing frequency [3]. In some cases the decrease in intensity is so great that certain burst maxima drop below the limit of detectability already at a wavelength of 20 cm. An impressive example of such a burst is given in Fig. 22. But according to the latest results obtained by our 1.25 cm receiver, most of the bursts of this type are weaker at 1.25 cm than at 3.2 cm. In other words, they must have a maximum intensity between 1 and 3 cm. They are similar to the bursts described above; only their maximum is shifted to shorter wavelengths. It is tempting to suppose that here we are confronted with a process that occurs only in the chromosphere and has no continuation in the corona.

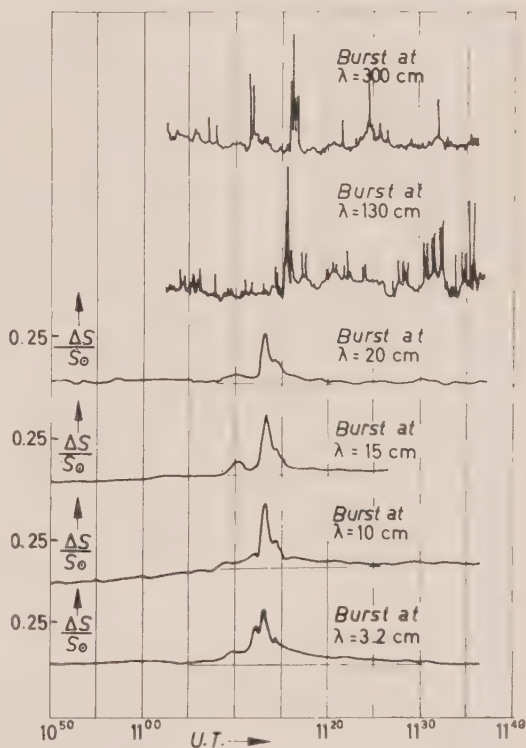
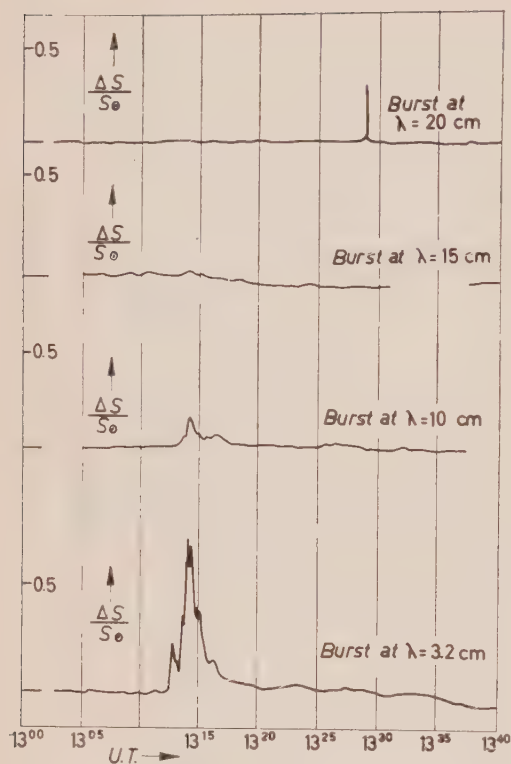


Fig. 21. - Records of the burst of 1957 Sept. 19 11h 07m U.T.



Thus we may distinguish two types of bursts according to their spectral characteristics.

When considering the behaviour of the maxima of a complex burst, one rarely finds that all of them behave in a similar manner. One mostly sees that one of the maxima of a burst increases toward longer waves, while another reaches highest intensity at a wavelength below 3 cm. Bursts of the latter kind lose their similarity in particular near the boundaries of the frequency range.

Fig. 22. — Records of the burst of 1957 Sept. 13 13^h 11^m U.T.

4. — The spectral intensity distribution.

The relatively smooth run of the records and the simultaneous occurrence of burst maxima on various frequencies in the centimetre range lead us to suppose that the radiation of the burst maxima is caused by an excitation process emitting a continuous spectrum in the whole range of frequencies concerned. For when reading off the intensity in the records, we find at a fixed moment for each frequency a definite value of intensity. In virtue of the similarity of the records we may connect the points in the plot of intensity *vs.* frequency, thus obtaining a more or less continuous spectral intensity distribution over the whole range.

If such a procedure is applied in the range of the burst maxima and if we choose the mean daily solar radiation as a unit, we can describe the intensity distribution in the spectrum by two curves, which are in full accordance with the typical behaviour of the single burst maxima described above.

Though such a representation tells us something about the frequency range within which we can observe a burst, it is of no particular value for a physical

interpretation of the process. For this purpose we have to turn to a uniform scale of energy. From the relative spectral intensity distribution we obtain by conversion with the daily values of solar radiation known for the different frequencies, the true intensity distribution of the burst radiation in watts per square metre and Hz. Fig. 23 shows the results for three typical distribution curves. Neglecting the continuation of curve *A* into the metre range, we find that curves *A*, *B* and *C* have a similar shape in the frequency range with which we are concerned. Curve *A* has a maximum in this range, after which the intensity falls off very slowly towards high frequencies. However, the curve falls off steeply towards the metre range. The broken curve is the maximum intensity of the burst in the metre range.

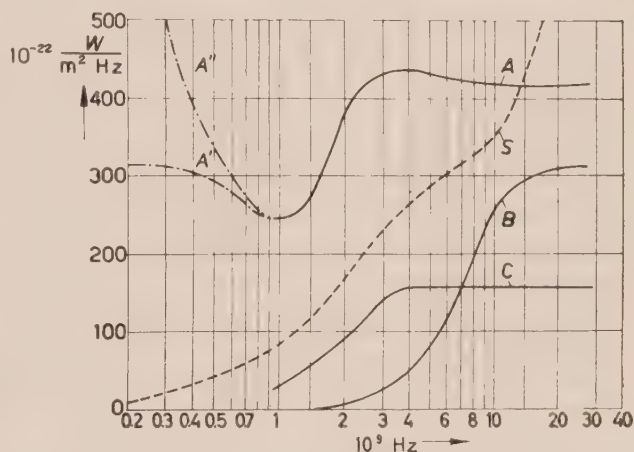


Fig. 23. — Observed energy distribution of bursts. *A*, *B*, *C*: energy distribution of different bursts. *S*: energy distribution of the sun at a sunspot number of $R=170$

Because of the different mechanism of emission, however, it must not be regarded as a continuation of curve *A* and therefore need not be considered here. Curve *C*, on the other hand, rises very steeply with rising frequency. Beyond 10 000 MHz the curve bends into a horizontal part—that means into a spectrum of equal energy. Curve *B* is situated between curves *A* and *C*.

An examination of a number of selected burst maxima shows that in addition to the three distribution curves mentioned above all possible transitions occur in close succession. The three spectral distribution curves which we called typical are therefore not to be regarded as basically different types; they rather represent the range of variation of the possible intensity distributions in the burst spectra.

We might rather state that the intensity distribution in the centimetre range is similar in all cases, save that the maxima, or better: the bending point of the curve, is displaced in the frequency range, as the case may be. Apparently we have to do with an intensity distribution of the following typical form: starting from a frequency of about $1 \cdot 10^9$ Hz there begins a continuum rising steeply to a maximum with rising frequency and from there proceeding

at almost constant energy towards high frequencies. Occasionally there is a broad emission band superimposed on this spectrum.

5. — Discussion of the spectrum.

Let us at this point interpose a consideration on the shape of the intensity curve in the spectrum.

Whereas in the range of metre waves in the majority of bursts we are concerned with a band emission, that is, a monochromatic emission, attributable to coronal plasma oscillations, it is evident that we have to suppose another mechanism of emission for the continuous emission of the centimetre wave range.

The slow monotonic decay of intensity at the end of major bursts described above gives rise to the supposition that perhaps we have to do with the thermic decay of a highly excited plasma. In this case at least part of the radiation would have to be of quasi-thermic origin [4].

What conclusions have to be drawn from such a supposition? Let us regard a thermally emitting volume with enhanced electron density and electron temperature as embedded in the upper edge of the chromosphere. Such a body of gas must have the following properties of emission: as long as the body of gas is optically dense, it must emit according to the Rayleigh-Jeans law; its intensity must rise with the square of the frequency. But as soon as the body of gas begins to become transparent for the higher frequencies, it will emit as a gray emitter. The emitted intensity is as follows:

$$I(\nu) = B(\nu, T) \cdot (1 - \exp[-\tau(\nu)]) ; \quad \tau(\nu) = \frac{\text{const} \cdot \alpha}{T^{\frac{1}{2}} \cdot \nu^2} \int N_c^2 dx ,$$

with $\tau \ll 1$ it becomes

$$I(\nu) = \text{const} \cdot \alpha \cdot T^{-\frac{1}{2}} \cdot \int N_c^2 dx .$$

The intensity falls behind that of the Planckian emission and passes over into a spectrum, the intensity of which is independent of frequency.

The spectrum of such a gas volume therefore has a close resemblance to the continuous spectrum of the bursts in the centimetre range. This applies in particular to the case that we take the spectrum of the monotonic decay at the end of big bursts. Thus the spectrum is another instance in support of our supposition of a quasi-thermal emission. For this part of burst radiation thermal emission seems very probable.

For a further discussion it is necessary to make a few theoretical considerations. We have to find out in what time the temperature of such a great

body of gas may decay, without its balance being disturbed. The time for the thermal decay depends on heat capacity and heat transport (conduction, convection and radiation). A calculation of the decay requires detailed data on the plasma of flare centres. But durations of the order of a few seconds up to several minutes seem to be plausible values for such a decay.

The spectrum of the burst peaks is also similar to the thermal emission of a gas volume; but for some bursts the intensity seems to drop slightly toward the higher frequencies, so that besides a thermal component we have to suppose an additional emission either by synchrotron radiation or by remainders of plasma oscillation as responsible for the emission of the burst peaks. Concerning a thermal emission also in the burst peaks we must ask ourselves what lengths of time are to be expected for a temperature distribution to take place under the conditions prevailing in the flare centres. The times in which a temperature distribution takes place can be characterized by the relaxation times due to single pulses or collective interaction. In the case of thorough interpenetration of an incident stream of particles with the plasma, the relaxation times should also be characteristic for regions of the size of the stream cross-section. Introducing into the usual formulae the parameters of the flare centres, we obtain times far below one second, in particular if collective interaction is taken into account.

In order to arrive at a definite solution of these problems it will be necessary to extend spectral investigations to the millimetre region. A confirmation of the spectrums of equal energy in the range of higher frequencies would be an essential point in support of the ideas developed in this paper. The measurements must also be supported by exact absolute measurements of radiation.

In that case the continuous spectrum of bursts in the range of centimetre frequencies would consist of two parts: the rise of intensity which represents a thermal radiation of an optically dense medium, and the later spectrum with equal energy of the gas volume which is optically thin at high frequencies. The bending point of the curve is determined by the electron density and temperature.

6. — Conclusions for the process of emission.

If it be the case that the continuous radiation of the centimetre waves range is of quasi-thermal origin—that is, if the radiation is generated in atomic processes—we have to conclude that in the place of origin there must prevail high electron temperature or at least high electron velocities.

Given a flare of importance 3 and a burst radiation double the total radiation of the sun, we then obtain a radiation temperature of 10^7 °K. Now it is obvious that not the whole area of a flare is involved in the emission pro-

cess; it is therefore probable that the electron temperature in the centre of the flare will be even higher.

A similar result is obtained if we disregard the temperature distribution and confine ourselves to suppose that there is a current of superthermic electrons in the plasma causing additional noise in the centimetre region. If we suppose that the flare region is optically thick, the electron energy must average $(10^3 \div 10^4)$ eV in order to produce the observed high radiation.

In accordance with our previous survey of typical burst forms we have to suppose that the emission takes place in pulses of the duration of the emission maxima. If the emission is to be attributed to superthermic electrons, then currents of superthermic electrons must also occur and decay in the rhythm of the burst peaks. In the case of pointed burst maxima they are accelerated within fractions of a minute, and just as quickly they transmit their energy to the other partners in the plasma.

7. - The region of emission of burst radiation.

For a further discussion of the process of emission it is important to know which region is mainly involved in the emission of centimetre radiation.

Starting from optical observations of flares we find that occasionally the emission of H_α is particularly strong in bright centres. We suppose that these centres may be of particular importance for the whole process.

In addition statistical considerations suggest the conclusion that the extent of the optical flare area is only of minor importance for the continuous radiation in the centimetre region of frequencies. If not, how should the following fact be explained? Let us take as an example the flares of importance 3 observed in the first six months of the International Geophysical Year, and let us take from the records the total energy transmitted at a wavelength of 3.2 cm, then we find that this energy oscillates between $40 \cdot 10^{-19}$ W s/m² Hz and $1000 \cdot 10^{-19}$ W s/m² Hz, whereas the area varies by no more than the factor 2.

It would therefore seem that the electron temperature or the energy of the electrons in the flare is of greater importance for the emission of centimetre waves than their number.

Direct measurements of the extent of the emitting area have only been made by KUNDU at Nançay [5]. By means of a two-element interferometer KUNDU determined the diameters of the emitting areas for several flares. His results may be summarized as follows:

- 1) In general the emitting region of bursts consisting of single sharp peaks has only little extent. KUNDU gives the diameter as $(1.1 \div 1.6)$ minutes of arc.

2) Bursts with a « postburst increase » of intensity indicate a small emitting region during the first peak, as is usual for such peaks. During their later part, that is, during the « postburst increase » of intensity, the emitting region seems to extend to twice or three times its size; the emitting region now has an average diameter of 2.5 minutes of arc.

3) In the case of bursts with gradual rise and fall of intensity the emitting region is given as 0.8 minutes of arc.

Considered on its own this result leads to the following consequence: If the above mentioned areas are compared with the optical areas of flares we find that the emitting areas at centimetre waves are twice as large as the optical flare areas. This fact makes an interpretation somewhat difficult. If we take the measurements for granted we cannot but conclude that the emitting area of the centimetre radiation is situated above the optical area of the flare. The emitting area of the centimetre radiation would have to be optically thin in spite of the high temperatures and therefore escape optical observations. Though such a concept would be in accordance with optical observations by TANDBERG-HANSEN and ZIRIN [6], ZIRIN [7] and TANBERG-HANSEN [8], who found that in the region of the flares excitation decreases strongly from higher to deeper levels, one should be careful to draw such a conclusion before there are measurements by interferometers with higher resolution.

8. — The relation between continuous emission and burst radiation at low frequencies.

Let us add a few concluding remarks on the relation between continuous emission in the centimetre range and monochromatic emission in the metre range of frequencies.

The emission of the two regions cannot only be distinguished in the spectrum by their character; there is also a clear break at about 1000 MHz. The intensity of the continuous spectrum falls off steeply towards low frequencies and in most cases ceases at about 1000 MHz, whereas on the other hand monochromatic emission begins at about 1000 MHz—occasionally already at 1500 MHz—its intensity rising towards low frequencies.

This peculiarity in the spectrum is the reason why the number of bursts when plotted as a function of frequencies presents a minimum at this point in the frequency range as was found by DAVIES [9].

Both parts of the spectrum seem to be highly independent of each other as to their occurrence; for if the emission of a flare is compared in both ranges we find that only a small part of the flare emits in the whole range—that is, in the centimetre range as well as in the metre range.

An equal number of flares emits only the centimetre continuum without

having any emission worth mentioning in the metre range. In our monthly reports on solar activity [10] we have denoted this group of bursts as chromospheric bursts. This designation is based on the idea that on the whole the centimetre radiation is generated in the chromosphere of the sun, and that the fact of there being no metre-wave radiation has to be taken as an indication

that the process in the flare region is not continued in the higher parts of the corona.

In contrast to these chromospheric bursts there are as many or even more cases in which the emission in the centimetre region is below the limit of detectability but where there is considerable emission in the metre range. The latter bursts we call coronal bursts.

The distinction between bursts according to their radiation in the centimetre and metre ranges provides not only a valuable characteristic for statistical studies; it also shows that the two mechanisms responsible for the emission must be highly independent of each other.

If we look for relations between the two

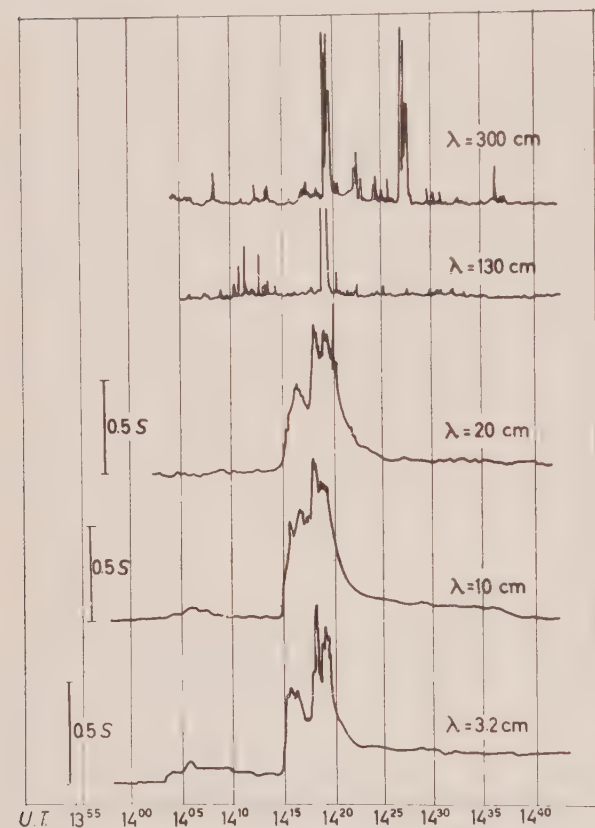


Fig. 24. — Records of the burst of 1957 Sept. 13
14^h 15^m U.T.

mechanisms of emission we shall mainly have to use bursts emitting in all the frequency ranges.

Of course it would be a fine thing if it were possible at once to decide into what type of burst of the metre range the continuous emission of single individual maxima will change. Unfortunately we do not possess sufficient material of spectrographic observations for an exhaustive study of this kind. We shall therefore have to base our ideas mainly on simple records.

A first consideration is concerned with the problem to find out certain

burst types of the centimetre region or certain maxima which are characterized by an emission in the metre range.

An inspection of the records shows that there is no type of burst in the centimetre range that would not occasionally be associated with an emission in the range of metre-wavelengths.

It seems that neither the shape of the maxima nor their succession in time has any influence on the continuance of the emission in the metre range.

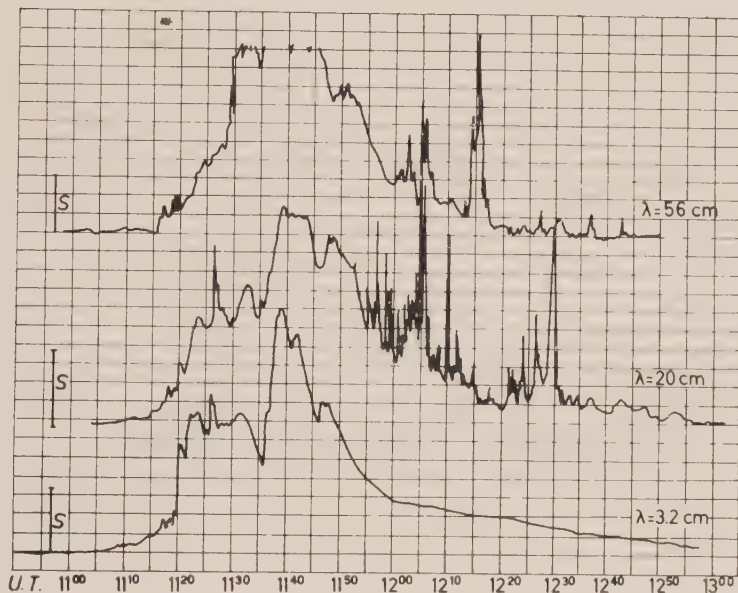


Fig. 25. — Records of the burst 1956 Nov. 7 11h 10m U.T.

Fig. 24 is to show a burst where a principal maximum seems to be the origin of bursts in the metre range: Fig. 25 illustrates a case where the monotonic decay at the end of the burst is evidently the starting point of phenomena resulting in bursts in the metre region.

As I said above, it is not easy to decide by means of records taken at different frequencies which type of Wild's classification occurs in each individual case. It was however possible to ascertain that Type I peaks as well as occasional Type II bursts and mainly Type III bursts occurred.

Conversely, if the list of Type III bursts observed at Freiburg is compared with our records of the centimetre range, one finds a majority of cases where Type III bursts were observed without there having been any effect in the centimetre range. From all this we must conclude that the emission in the metre range of frequencies must certainly be attributed to a process which is

only very loosely related to the mechanisms of emission in the continuous spectrum of the centimetre range.

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IV.

A Comparison between the Continuous Spectrum of Flares in the Centimetre Region and Optical Observations.

1. - Introduction.

After APPLETON and HEY [1] had first discovered that the burst radiation in the radio frequency range is connected with the flares of the sun, repeated attempts were made to establish a relation between the form of radio frequency radiation and light curves in the optical region. But such attempts have not been very successful. Only in some cases was it possible to state that outstanding events in the radio frequency range coincided with certain phases of the optically observed forms. Nowadays this meagre result does not seem surprising any longer, since it was mainly the burst radiation of the metre-wavelengths, on which comparison was based in studies of that kind. According to our present ideas the metre-radiation is excited by secondary processes high above the optical flare region in the corona. Its emission, above all, depends on the conditions prevailing in the corona, whereas the optical radiation has its origin at the level of the chromosphere and supplies us with data on processes at a much deeper level of the solar atmosphere.

It was only possible to identify streams of particles observed at the solar limb as sources of radio frequency radiation. In several cases GIOVANELLI

and ROBERTS [2] thus identified ejected surges of prominences with bursts of type II.

Touching this problem again, I should like to start from my previous lecture. We had concluded from the continuous emission of the centimetre range that emission is generated by a high temperature electron gas or by a stream of highly accelerated—superthermic—electrons. As the origin of the radiation we had to regard the upper chromosphere or the upper border region of the chromosphere.

2. – The continuous emission in the optical region.

Let us now test the question: If there exists such a plasma with 10^7 degrees of electron temperature in the upper chromosphere, what follows for the optical region? What optical observations ought to be possible?

In the first place we must expect that the continuum observed in the centimetre region extends to the optical region. Unfortunately it is very seldom that we can observe a continuous emission in the visible region, so that for the time being we cannot say anything definite on a possible connexion. Of the number of eruptions that have also been observed in white light, compiled by U. BECKER [3], only the three flares of 1956, Aug. 31, of 1958, March 23, and of 1958, March 30, were also measured in the centimetre range at the same time. In these cases it can be seen that the time of the flashing-up of the continuum coincides with the maximum of the centimetre continuum.

If in these cases the intensity of the continuum in the centimetre range is compared with the intensity in the visible region, the following data are then obtained:

Date	$\lambda = 3,2 \text{ cm}$	$\lambda = 5000 \text{ Å}$
1956 Aug. 31	$2.3 \cdot 10^{-19} \text{ W/m}^2 \text{ Hz}$	$(3 \cdot 10^{-18} \div 2 \cdot 10^{-17}) \text{ W/m}^2 \text{ Hz}$
1958 March 23	$1.5 \cdot 10^{-19} \text{ »}$	—
1958 March 30	$0.3 \cdot 10^{-19} \text{ »}$	—

The intensity of the continuum in the visible region exceeds that of the centimetre range by a factor of $10 \div 100$. This difference is probably due to the higher absorption coefficient of the plasma in the optical region. A study of the continuum in the optical region would be useful for an understanding of the process. I cannot tell, however, what chances there are in this respect. Perhaps it will be possible, at least in the case of limb eruptions, to obtain information on the intensity distribution and absolute intensity.

3. - The linewidth of H_{α} .

Highly accelerated electron gas ought to become apparent also in different excitation processes. We possess only a limited number of optically highly resolved spectra, so that we are not yet in a position to carry out a comparison between the line intensity of highly excited lines and the intensity of the centimetre continuum.

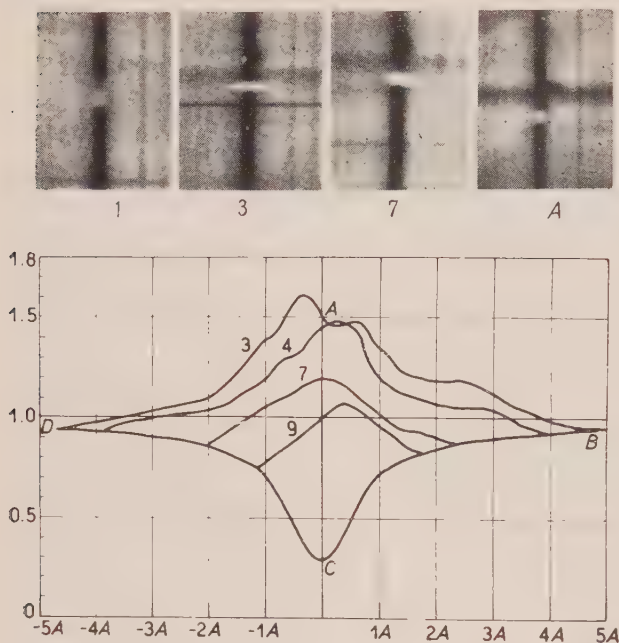


Fig. 26. - Spectra of H_{α} and H_{α} -profiles of the flare 1957, July 3. (1: 7^h 40^m; 3: 8^h 39^m; 4: 8^h 40^m; 7: 8^h 52^m; 9: 9^h 40^m) after COMPER [5].

We only possess measurements of the intensity and of the linewidth of H_{α} . Now, intensity measurements taken in the middle of the H_{α} -line are not very suitable for a comparison, for the flare area is optically thick in H_{α} . We therefore see only a partial layer of the events. On the other hand the flare area is optically thin in the centimetre range in most cases. For this reason intensity measurements taken in the line wings—or linewidth measurements, have to be given preference for the purposes of a comparison.

It is known that hydrogen lines in the flash phase of flares have extraordinarily broad wings, the origin of which is still uncertain. Fig. 26 shows H_{α} of the flare 1957, July 3. In the following we shall have to pay particular attention to those unusual linewidths.

A large number of linewidth measurements have been made by the Ondrejov Observatory. Dr. SWESTKA, of that institute, was so kind to let me have the linewidth measurements for 20 selected flares of the year 1957, in addition to those already published [4]. In some other cases we relied on measurements by the Fraunhofer Institute, or those by COMPER [5] of the Kanzelhoehe Observatory.

4. — Comparison between linewidths of H_{α} and the intensity variation of 3.2 centimetre radiation.

If the linewidths measured and the burst record of the centimetre range are plotted in one diagram one sees clearly that there is a similarity in the shape of the curves.

Of course it cannot be expected—particularly in the case of large flares—that the run of the curves will be parallel in all the different cases. The linewidths measured refer largely to a limited part of the flare area, whereas the

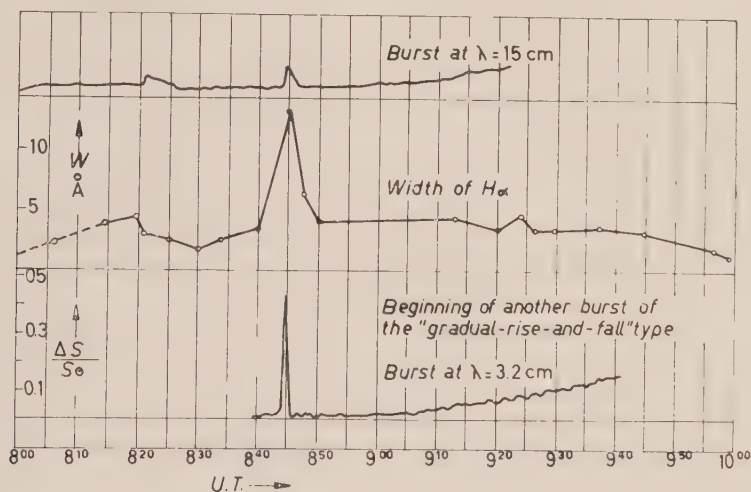


Fig. 27. — Flare of 1958, March 30 (importance 1+). Burst recorded at 2000 and 9400 MHz together with linewidth of H_{α} .

three centimetre radiation represents the integral emission over the whole area. It has further to be taken into consideration that linewidth measurements are not easily made and depend on the image quality as well as on the perception of the observer. Irrespective of these restrictions, the curve of linewidths and the 3 cm records have on the whole been similar in all cases.

It is a fine instance of this similarity that also the well known burst types of the centimetre range, such as those classified by COVINGTON, have a corresponding form with regard to their linewidth. Let us convince ourselves of this fact by a few examples.

It is difficult to find suitable examples for the type of single peak. Such a burst takes place within a few minutes; the corresponding optical phenomenon may easily escape observation. Nevertheless there are convincing examples.

Fig. 27 shows the flare 1958, March 30, which was also seen in integral light by U. BECKER at Freiburg. The flare started at 7 h 55 min without a strongly marked linewidth of H_α . Only at 8 h 44 min does the linewidth rise considerably, reaching about 13 Å, then drops with the same rapidity to decay for more than an hour. The 3.2 cm record started at 8 h 40 min. At this time or a little earlier—between 8 h 25 min and 8 h 40 min—there was no additional radiation worth mentioning, as may be inferred from a comparison with 10 cm and 15 cm records. At 8 h 45 min there is a sharp peak, afterwards decaying until the previous level of radiation is reached again. Later we see a slow rise of intensity, due to a following burst of the « gradual-rise-and-fall » type, with which we are not concerned here.

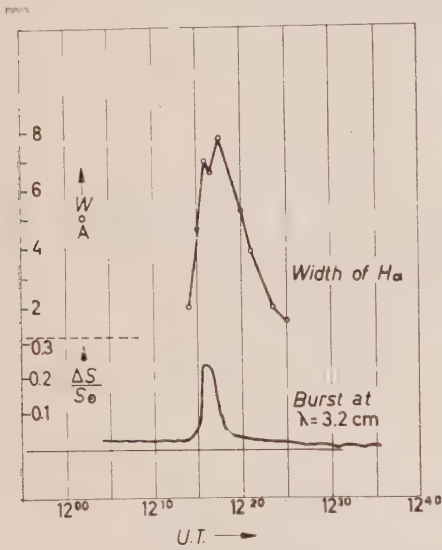


Fig. 28. — Flare of 1957, December 12 (importance 1). Burst recorded at 9400 MHz together with linewidth of H_α .

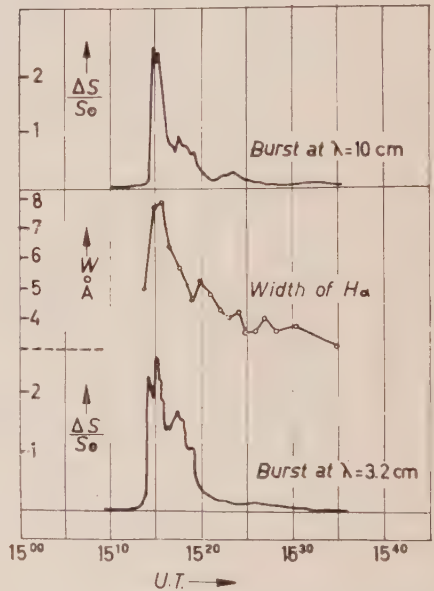


Fig. 29. — Flare of 1957, September 12 (importance 3). Record of the burst at 3000 and 9400 MHz compared with linewidth of H_α .

Let me remark that a Mögel-Dellinger effect also sets in at 8 h 40 min with a duration of about 10 minutes.

The figure also shows the recorded radiation at 15 cm wavelength in comparison. Fig. 28 gives a flare of importance 1 of 1957, December 12. At 3.2 cm, the flare has a broader peak with a halfwidth of circa $1\frac{1}{2}$ minutes. The corresponding linewidth increases considerably but in comparison with the maximum of the centimetre records, its maximum evidently occurs with a delay

of 1 minute. It seems that a brief delay is found with all burst peaks of short duration.

Very instructive examples are those for the single peak type with increased

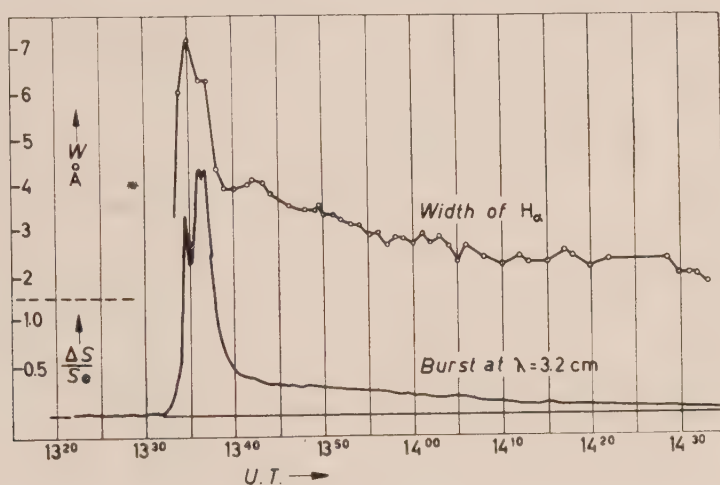


Fig. 30. - Flare of 1957, September 21 (importance 2). Record of the burst at 9400 MHz compared with linewidth of H_{α} .

postburst level of radiation. Fig. 29 shows the flare 1957, September 12. The linewidth diagram follows the 3 cm and 10 cm records very closely. The same is the case with the flare 1957, September 21. Here too, the measured linewidth

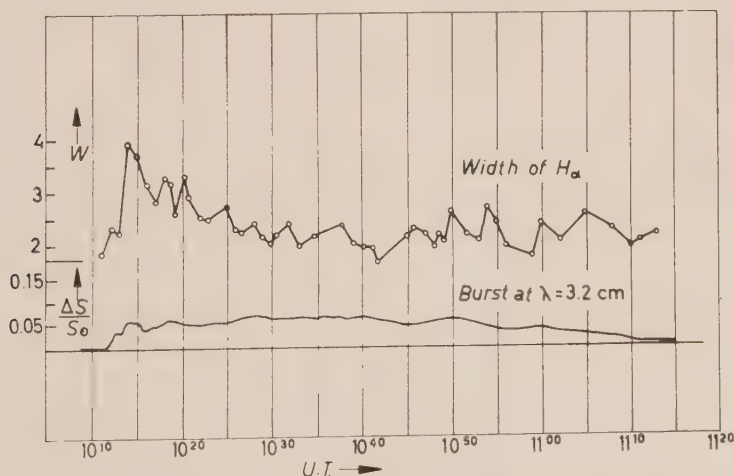


Fig. 31. - Flare of 1956, October 11 (importance 2+). Record of the burst at 9400 MHz together with linewidth of H_{α} .

runs parallel to the 3 cm record (Fig. 30). Several other examples have been found for this type in particular. Also in the case of the «gradual-rise-and-fall» type the similarity between the linewidth measured and the 3 cm records can be illustrated by good examples. Fig. 31

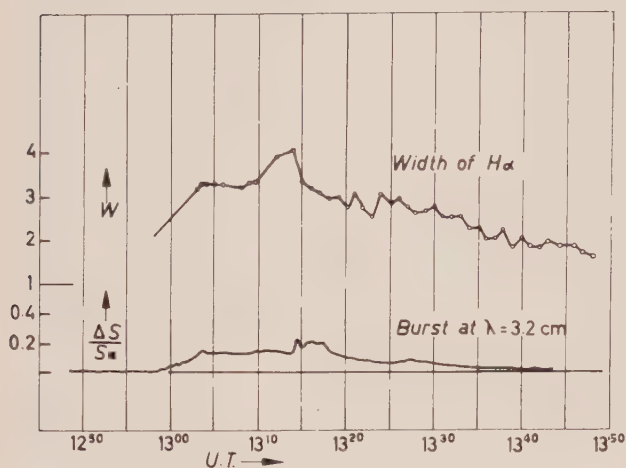


Fig. 32. — Flare of 1957, July 7 (importance 2). Record of the burst at 9400 MHz together with linewidth of H_{α} .

shows such a flare. At its beginning there is still a rather steep rise, but then it extends for over an hour with almost equal intensity. In this case the linewidth at the beginning of the burst seems to be somewhat greater than would correspond with the burst diagram. The «gradual - rise - and - fall» in Fig. 32 is very characteristic and the similarity is satisfactory.

A certain similarity can also be found in the case of very large outbursts with complex forms. A fine example is supplied by the burst 1957, July 3

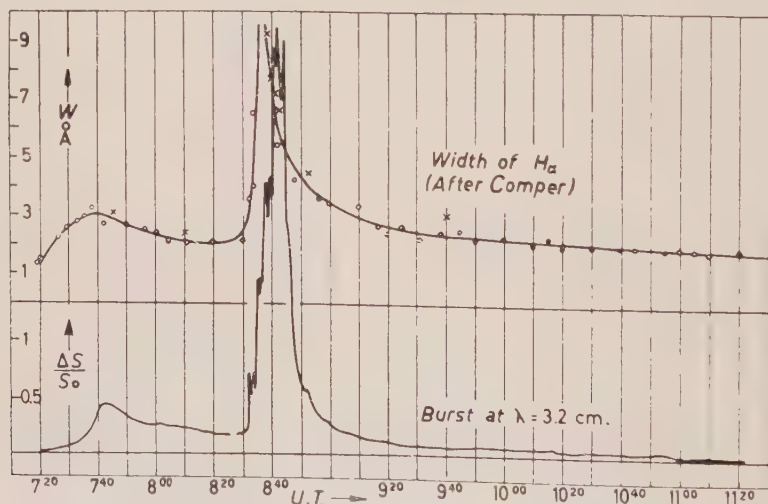


Fig. 33. — Flare of 1957, July 3 (importance 3). Record of the burst at 9400 MHz together with linewidth of H_{α} .

(Fig. 33). In this case very exact linewidths were measured by COMPER [5]. Here too, the form of the 3 cm records is similar. Lastly Fig. 34 shows the large burst of 1958, March 23, which was also observed in integral light at Freiburg and Zürich. The curve of the linewidths measured by U. BECKER does not follow exactly the different peaks of the 3 cm curve, but on the whole the similarity between linewidth and 3 cm record is close enough.

In a total of some 30 flares examined there were practically only two cases in which greater discrepancies between linewidth and centimetre records could

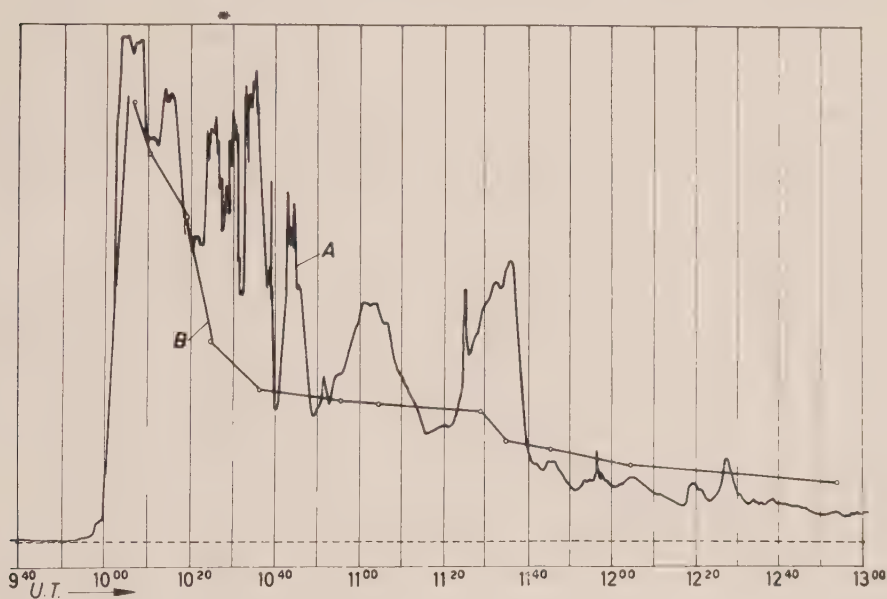


Fig. 34. - Flare of 1958, March 23 (importance 3). Burst recorded at 2000 MHz together with linewidth of H_{α} .

be found. One of those flares was the big flare of 1956, November 20, where the maximum of the 3 cm record occurred much later than the maximum of the linewidths given by Ondrejov. In the case of big flares—as we said above—it is not quite certain whether the measurements of linewidths really catch the main centre. However, the different behaviour in the two cases mentioned need not bother us at the present moment.

Now the result may be summarized as follows: The linewidth diagram and the records of the centimetre continuum confirm a similarity of the underlying processes.

When there is an increase in the centimetre radiation a considerable broadening of the H_{α} -linewings or of the hydrogen lines in general sets in. Conversely, it may be stated that flares with a continuous emission in the centi-

metre range also have those particularly extended wings of the hydrogen lines. Perhaps the centimetre radiation is connected with the phenomenon which SEVERNY [6] describes as «Moustaches» of H_α . Only in the case of the sharp peaks of the 3 cm radiation does the width of the hydrogen lines seem to follow with a delay of 1 to 2 minutes; concerning this point we shall have to wait until there will be more exact measurements.

5. — Quantitative relation between the maximum linewidth and the maximum intensity of the centimetre radiation.

Because of the similarity between the curves of the intensity of centimetre radiation and that of the linewidth of H_α , it is reasonable to suppose that there exists a proportionality between the intensity of the centimetre continuum and the linewidth, at least in the single flare. Let us therefore try to find out whether such a relation exists in general.

Now such a general proportionality—though probably existing—is very hard to ascertain by observations. Centimetre records supply an integral radiation value averaged over all emitting areas of the flare. Linewidth measurements, on the other hand, yield a value which is only valid for the part of the flare focused on the slit of the spectroscope. Supposing the radiation of the total flare area A to be nearly uniform, the centimetre radiation would have to be related to the unit of flare area, which in turn would have to be compared with the linewidth W .

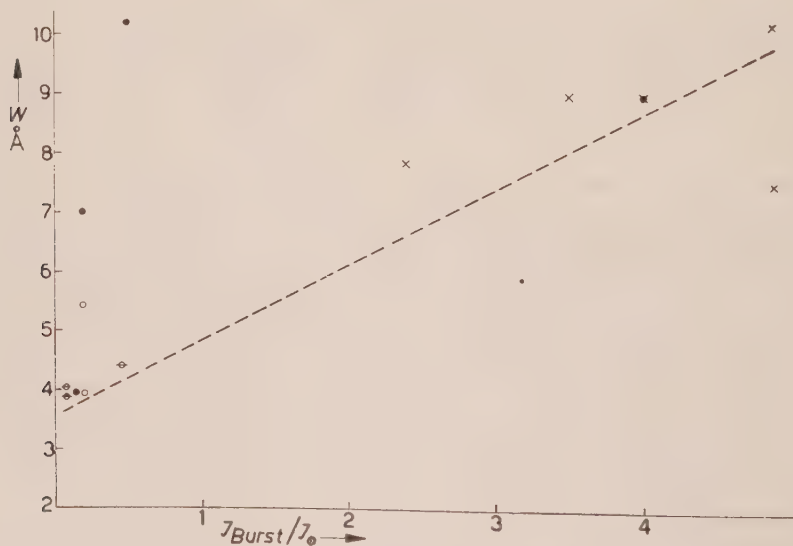


Fig. 35. Maximum linewidth *versus* maximum intensity of bursts at 9400 MHz.

Then we could take

$$I_{\text{cm}}/A \approx W$$

thus combining somewhat corresponding data in a relation.

Unfortunately the existing material of observations is not comprehensive enough to encourage such an attempt. So we contented ourselves with dividing the recorded flares into classes of importance wherever there were measurements with regard to their centimetre radiations as well as linewidths. Fig. 35 shows the respective linewidths as ordinates *versus* the centimetre radiation as abscissa, giving the flares of importance 3 as dots, those of importance 2 as crosses, and those of importance 1 as circles. The distribution of the points in the diagram shows that the presumed relation seems to exist. For flares of importance 3 a straight line has been drawn through the points. From the diagram we can read the following statements:

1) Flares with a linewidth smaller than $3.5 \text{ \AA}$ do not produce any effect in the centimetre range; conversely, all flares not emitting in the centimetre range generally have no linewidths larger than $3.5 \text{ \AA}$.

2) Starting from $3.5 \text{ \AA}$ the maximum burst radiation in the centimetre range increases monotonically with increasing linewidth.

At least for a marked burst of importance 3 the diagram supplies the following average characteristics: if such a flare emits a maximum centimetre radiation of $300 \cdot 10^{-22} \text{ W}$ per square metre and Hz, the width of the hydrogen line in the flash phase will be circa $10 \text{ \AA}$. This value will be used in the following discussion.

6. - Some remarks concerning the emissivity of the flare area.

Before we enter into a discussion of the result referred to above, let me point out the fact that we found nothing but a very loose relation between the extent of the flare area and the total emitted energy in the centimetre range. Flares of importance 3 with almost equal areas may differ by a ratio of 1 to 100 as to their emitted energy in the cm region. The flare area is therefore of minor importance for the emission of centimetre-waves. On the other hand the close relation between linewidth and maximum intensity in the centimetre range is a further indication that the centimetre-radiation has to be attributed to a high temperature electron gas and that the electron energy has to be regarded as the decisive factor for the emission in the centimetre range.

7. - Conclusions.

The results thus far allow us to draw a few conclusions which are important for an understanding of the processes in a flare.

1) The extraordinary width of the hydrogen lines in flares has presented some difficulty. The broadening of the line occurs only for hydrogen; the broadening is smaller for helium lines and negligible for metal lines. It is this difference in the behaviour of the elements which seemed to make it improbable that this broadening should be a Doppler broadening, that is, a thermic movement of the hydrogen atoms. One was therefore led to believe that it was necessary to resort to the Stark effect for an interpretation of this phenomenon.

If, however—as in the previous lecture—we attribute the continuous emission in the centimetre range to highly accelerated electrons—that is, super-thermal electrons—the close relation between the hydrogen linewidth and emission in the centimetre range imposes the supposition of thermic broadening also in the case of the hydrogen line. In that case, however, we have to answer the question why the broadening of the lines is not observed in the case of metals.

Well, the flare area is optically thin in the visible region. It is therefore possible that the metal lines are produced at a greater depth in the solar atmosphere—that is, at lower levels of the chromosphere—where there is no increase in temperature. As we know from optical observations, the excitation temperature in flare areas increases heavily from within to without, which would be in accordance with the above idea.

2) From Fig. 35 we had deduced that an average flare of importance 3 has a maximum emission of about $1200 \cdot 10^{-22}$ W per m^2 and Hz, and that the same flare must produce a linewidth of $9 \text{ \AA}$ in the flash phase. We can use this fact to determine the electron temperature on one hand, on the other we can derive the temperature or kinetic energy of the hydrogen atoms from the width of the hydrogen lines. Doing this, we find a temperature of $2 \cdot 10^7$ degrees for the electrons, and a temperature of $6 \cdot 10^6$ degrees for the hydrogen atoms. The lower temperature of the hydrogen might also be attributed to the fact that the hydrogen emission takes place in a deeper layer of the chromosphere than the centimetre radiation.

On the other hand the difference of temperature observed for electrons and ions is of great similarity with the processes in low pressure discharge tubes. There the energy supply takes place mainly through the electrons. We therefore find a higher electron temperature than would correspond to the temperature measured spectroscopically. Would it not be possible in the

case of flares, too, that the energy supply takes place primarily through the electrons and is only then transmitted to the other ions of the plasma? What ever it may be, it seems to me that these observations provided us with some new aspects on the flare process.

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V.

**Relations between the Continuous Radiation of the Flares
in the Centimetre Region and the X-Ray Component Producing
the Ionization in the Ionosphere.**

As has long been known, the flare area is not only the source of radio frequency emission, but also of a high-energy electromagnetic radiation, occurring obviously in a wide spectral range from the far ultraviolet up to the X-ray region. It is this radiation in particular with which we shall concern ourselves in the following. For a long time, we had only indirect proofs of its existence. This radiation produces an additional ionization in the lower ionosphere with a series of secondary effects. We ascertain it in the sudden strong absorption of short radio waves—the Moegel-Dellinger effect or the «Short Wave Fade-out» (S.W.F.)—in the increase of absorption of the cosmic radio noise at about 20 MHz (S.C.N.A.)—in the sudden increase of intensity of field strength at very long wavelengths—mostly observed as «Sudden Enhancement of Atmospherics» (S.E.A.)—in the «Sudden Phase Anomalies» in the longwave range (S.P.A.)—and in the magnetic effect—the «crochet» of this additional ionization.

Recently this radiation has been proved directly by FRIEDMAN a.o. [1, 2] launching rockets. The measurements with rockets have given us some first clues on the shortwave end of its spectrum, which is situated at about 2 Å.

Moreover the flare area sends out a slow corpuscular stream whose existence as yet can only be ascertained by indirect methods. Geomagnetic storms,

disturbances of the $F2$ layer of the ionosphere, and aurorae are indications of this radiation.

Finally in rare cases the flare sends out cosmic rays. As yet there have been four cases in which major outbursts of cosmic rays could be clearly related to flares on the sun.

1. – Statistical investigation of the relations between the centimetre-radiation and the X-ray component producing the ionization in the ionosphere.

That the different kinds of radiation have their origin in the flare area has to be concluded from the coincidences of the mentioned secondary effects with optical flares. Besides this we know practically nothing of the inner relations of the processes releasing the different kinds of emissions.

Surveying the observations of single flares with their secondary effects, we can state—with the exception of very intensive phenomena—the one flare causes a characteristic S.W.F., that is, a heavy ultraviolet or X-ray pulse, but hardly any of the other effects. Another flare produces a large stream of particles and causes a geomagnetic storm without there having been a particular S.W.F. A third flare has an effect only in the range of radio frequencies without any other attendant phenomena.

1.1. *The statistical frequency of the effects.* – Even the statistical frequencies of the different effects caused by flares are only partly known. Of course these data depend on the properties of the effect used as an indicator and on the sensitivity of the equipment. For the X-ray component we find that

10 to 15% of the flares observed are associated with a Mögel-Dellinger-effect [3, 4];

30 to 50% of the flares observed produce an S.E.A. according to investigations by KŘIVSKÝ and RUŽIČKOVÁ [5];

30% of the flares produce a S.P.A. [6]; and

at best 5% of the flares observed produce a «crochet».

Taken as a whole, longwave effects seem to be the most sensitive method of ascertaining an enhanced electron density in the lower ionosphere and hence the occurrence of the X-ray component.

With some precaution we can say that about 20 to 40% of the flares send out an X-ray pulse.

As concerns corpuscular disturbance our knowledge is even more incomplete. About 10% of the flares are connected with corpuscular radiation dis-

turbing the ionospheric F -layer or causing a geomagnetic storm. Major geomagnetic disturbances and connected auroral effects are still more rare.

Less than 0.1 per thousand cause an enhanced emission of cosmic rays.

The true inner relation of these phenomena, as I said, is still a mystery in many respects. Radio-frequency measurements have supplied further important arguments for an attempt at their clarification.

12. *A subdivision of the flares by their radio-frequency emission.*—As we saw in the third lecture the radio frequency emission of the flares is due to two basically different mechanisms of emission. There is

- 1) a continuous emission in the centimetre range of frequencies, which at least partly must be interpreted as an emission caused by supra-thermal electrons;
- 2) a monochromatic emission in the range of metre-waves, which in general we think to be a radiation of the coronal plasma.

The rarely occurring continuous emission in the metre-wave range (type IV burst) will be neglected in our considerations.

If we take into account that the different frequencies originate at different levels above the solar photosphere, the continuous emission of the centimetre range must take place in the upper chromosphere or in the upper border region of the chromosphere—that is approximately in the optical flare region—while the emission of the metre-wave range is generated high above the flare region, in the corona, at an altitude of 50 000 to 200 000 km above the photosphere.

Thus there are two characteristics enabling us to come to a decision on the process itself as well as on the location of the event.

Considering the radiation of different flares in the radio frequency range under this point of view, we state the following differences:

A) Certainly there are flares emitting only in the centimetre range—that is, occurring in the chromosphere only. (As the monochromatic radiation in the corona seems to be easily to excite, we have to conclude that in this case the flare region does not influence the high corona, in other words, that no particularly large stream of particles is expelled by the flare regions.)

B) On the other hand it is certain that there are flares emitting a continuum in the centimetre range, but also continuing in the metre range. In this case the flare region additionally sends out a corpuscular radiation penetrating high up into the corona, where it releases the metre-wave radiation.

C) There are flares which do not emit a centimetre continuum, but have a strong emission in the metre range. Here we have to do with a

mechanism of excitation generating an emission only at high altitudes in the corona.

D) Finally we ascertain a group of flares having no effect at all in the range of radio frequencies.

We have thus laid the foundation for a successful attempt of a classification of the flares.

1.3 Some remarks on the frequency of coincidences between flares and bursts in the range of centimetre waves: For the purpose of classification HACHENBERG and KRÜGER [4] used the flares of the first six months of the International Geophysical Year. According to the maps of the sun published by the Fraunhofer Institute, a number of 1396 flares was observed during the periods in which our radio frequency receivers were also in operation. In the same period we recorded 395 bursts in the centimetre range, only 280 of which coincided with the observed flares. Therefore, certainly 71% of the bursts have their origin in the flare region.

On the other hand, if we suppose that all bursts of the centimetre range are connected with a flare-like phenomena, then 29% of the flares would have escaped optical observation. This percentage seems to be rather high, considering that the sun is constantly watched by a great number of observatories. The relatively high percentage confirms our supposition that part of the weak bursts are due to very small subflares that may easily escape observation because of their little area.

Relative to the flares these figures tell us that only 20% of the flares are accompanied by an effect in the centimetre range, or, speaking correctly, they are accompanied by a burst of intensity $J \geq 0.04 J_{\odot}$. But since the number of recorded bursts increases considerably with decreasing maximum intensity it is probable that the percentage of coincidences will rise, if the sensitivity of the centimetre radiometers can be increased.

1.4. Distribution of the flares between the groups A to D. — If now we distribute the 1396 flares between the above groups we get the following picture:

About 73% of the flares have no effect in the range of radio frequencies. They have to be arranged under *D* of Table I. Coincidences between flares and weak type I peaks have been excluded. Type I peaks frequently occur at times when the sun is certainly free from flares. In many cases their coincidences with flares must therefore be regarded as accidental (see also [7]).

Of the 280 flares connected with centimetre bursts 146 produced an emission in the range of centimetre waves only, in these cases the underlying processes must have taken place predominantly in the chromosphere.

TABLE II. — *Distribution of flares according to their radiofrequency emission.*

	<i>A</i> flares with cm continuum only	<i>B</i> flares with cm continuum and radiation in m range	<i>C</i> flares with emission in m range only	<i>D</i> flares without any effect
1396 flares of 1957 II	146 10.4%	134 9.6%	96 [396] 6.9%	1020 73%
of this 280 flares with S.I.D.	90 62%	95 71%	1 1%	12 1.2%
flares with cor- puscul. radiation	—	C.R.	C.R.	—
flares with cosmic rays	—	C.R.	—	—

134 flares effected bursts in the centimetre range that could also be observed in the range of metre-waves. These flares caused the excitation of a characteristic radiation in the corona as well.

Lastly records made at Nera, Potsdam and Blindern in the same period contained 396 bursts emitting only in the metre range.

15. *Distribution of flares associated with S.I.D. between the above groups.* — In the period of observation there occurred 231 cases of enhanced ionization in the *D*-layer—S.I.D.—that could be regarded as certain. In order to exclude erroneous observations by long-period fadings or local changes in the propagation conditions, the S.I.D. were regarded as certain only if they had been reported by two different stations or if they had been found by two independent methods of observation.

If we now examine the percentages by which those S.I.D. are arranged in the above groups, we find only 12 cases where the respective flare has no noticeable emission in the range of radio frequencies and still produces a S.I.D. On the other hand, 90 cases coincide with the 146 flares producing a burst in the centimetre region, and 95 cases coincide with the 134 flares accompanied by a burst in the centimetre ranges as well as in the metre range. Finally there are two cases belonging to the last group. In addition to this, Table II contains the percentages of the flares in the respective group which also produce a S.I.D. But before we proceed to a discussion of the results, let us first include the flares with corpuscular disturbances in our scheme.

1'6. *Distribution of the flares producing a disturbance by corpuscular radiation in the ionosphere.* — It is not always easy to correlate the observed ionospheric or magnetic storms with preceding flares. DODSON and HEDEMAN [8] found that flares of groups *C* and *D* are preferably connected with corpuscular disturbances. Since the percentages are uncertain, we have denoted the flares in Table II only by C.R. (corpuscular radiation).

1'7. *Cosmic radiation.* — Flares that are also the origin of cosmic rays belong to the major events among flares. They are generally connected with all effects and therefore must be arranged under group *B*.

1'8. *Conclusions.* — A look at our Table shows that S.I.D.—that is the X-ray component—are closely related with the flares emitting a continuum in the centimetre-wave range. Taking into account the very small percentages of groups *C* and *D*, we can draw the following conclusion:

1) Only those flares producing a burst in the centimetre range are likely to cause an X-ray pulse.

2) This close relation is equally valid for the different types of bursts. The type of the impulsive peaks as well as the «gradual-rise-and-fall» type have the same percentage of cases connected with S.I.D.

3) The great number of coincidences in group *A* indicates that the ionizing radiation that generates the S.I.D. is also sent out by the flares apparently taking place in the chromosphere exclusively. The radiation is likely to originate at a level of the chromosphere about 3 000 to 10 000 km above the photosphere.

4) Concerning the slow corpuscular radiation we find that it is ejected predominantly by the flares with a strong emission in the metre range—or in other words, the metre-wave radiation of the corona above the flare region is the first indication of an emitted corpuscular radiation.

2. — The relation between X-radiation and centimetre-wave radiation in single phenomena.

The close connexion between the centimetre-wave continuum and the ultra-violet or X-ray component as revealed by a statistical examination is not very surprising, after all. We had supposed that high-energy electrons—perhaps superthermal electrons—are responsible for the generation of a continuous emission in the range of centimetre-waves. It suggests itself to regard these electrons as responsible for the excitation of X-rays, too, either as a mono-

chromatic radiation of the X-ray levels in the atoms of metals or as a « bremsstrahlung ».

From this it follows necessarily that the X-ray intensity must be in approximate accordance with the intensity curve of the centimetre-wave radiation. This relation can be checked. We are now going to examine it a little more closely [9].

21. *How a comparison would have to proceed in principle.* — As was stated above, the ultraviolet or X-ray components of the flare radiation cannot yet be measured directly. Measurements made with rockets have practically supplied single points of the radiation intensity; the required continuous curve for the whole time of the flare cannot yet be measured.

Thus we are left to derive the curve in an indirect way by determining the electron density in the *D*-layer of the ionosphere. Among the known effects of radio propagation depending on the electron density of the *D*-layer, the sudden absorption of short waves—M.E.D.—or the absorption of cosmic radio-frequency radiation are suited for deriving the additional electron density in the *D*-layer during a flare.

In order to derive the additional electron density we approximate the respective part of the *D*-layer by a Chapman layer. It would be possible to do without this model, but it allows some convenient simplifications for the calculation. In the model layer the electron density in the maximum of the layer, *N*, is proportional to the absorption *L* in the total layer. Thus we have

$$L \sim N.$$

Or the ratio of the additional absorption ΔL to the undisturbed absorption L_0 at the time of the effect is

$$\frac{\Delta L}{L_0} = \frac{\Delta N}{N_0},$$

equal to the enhancement of electron density ΔN divided by the undisturbed value of electron density.

On the other hand, additional free electrons—in the case of incident X-radiation—are produced proportionally to the intensity of the incident radiation

$$q \sim J.$$

Now electron production and electron density are linked by the continuity equation. We have

$$\frac{dN}{dt} = q_0 - \alpha \cdot N_0^2,$$

where α denotes the effective recombination coefficient.

If the daily variation of the electron density is taken as a constant for the time of the flare, then $q_0 = \text{const.}$ The change of electron density $\Delta N/N_0 = n$ then becomes the equation

$$\frac{dn}{dt} = \alpha \cdot N_0 (\mu - 2n + n^2),$$

where $\mu = \Delta q/q_0 = \Delta J/J_0$ signifies the X-radiation measured in units of the normal radiation.

Since the terms dn/dt and n of the differential equation are known from the measurement of the absorption and $\alpha \cdot N_0$ is also known from ionospheric data μ can be calculated numerically.

Or the absorption variation may be approximated by the function

$$n = n_{\max} \cdot \tau \cdot \exp [1 - \tau] \quad \text{with} \quad \tau = \frac{t}{t_0}$$

Inserting this into the differential equation we obtain

$$\mu = \frac{n_{\max}}{\alpha N_0 t_0} \cdot \exp [1 - \tau] [1 + \tau(2\alpha N_0 t_0 - 1) + \alpha N_0 t_0 n_{\max} \tau^2 \cdot \exp [1 - \tau]]$$

and for the maximum occurring at $t = 0$ we have the relation

$$\mu_{\max} = \frac{n_{\max} \cdot t_0}{\alpha \cdot N_0 \cdot t_0}.$$

In any case the solution indicates clearly that the ionizing radiation—that is, the X-radiation, begins with a flash phase and then decays. It further shows that the prolonged decay of the absorption in the case of a Mögel-Dellinger effect must mainly be attributed to the slow recombination in the *D*-layer. The discussion of the solution further shows that conclusions on fine details of the radiation curve may not be drawn from the absorption curve because of the «sluggishness» of the ionosphere.

Further, it must be stressed that the single-layer model used here is very simplified. The real conditions may be far more complex through the fact that the level of maximum S.I.D. absorption in the *D* region may be different from the level of maximum undisturbed absorption. Finally, the real absorption takes place in a large height interval with a strongly varying recombination coefficient.

2.2. *Absorption measurements.* — An exact experimental determination of the absorption variation is highly difficult.

There are several ways of determining the absorption. The method used most frequently consists in recording the echo of a shortwave transmitter—if possible in the band of 2 to 4 MHz—reflected by the ionospheric *E*-layer. The waves are recorded after having twice passed the absorbing *D*-layer. Changes in absorption become at once apparent as decreased field intensity.

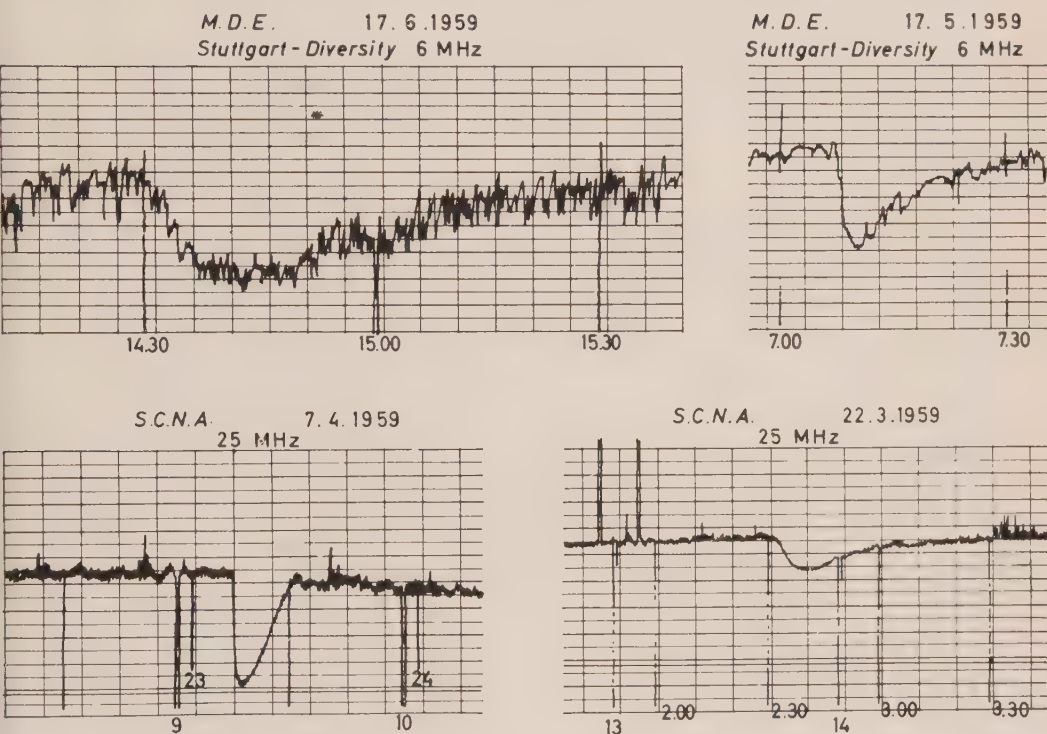


Fig. 36. Typical records of sudden increase of ionospheric absorption of short radio-waves.

The fadings reduce the exactitude of the measurements, making an exact determination of the absorption variation of weak effects even problematical. In order to compensate this disadvantage we have made arrangements for diversity reception with three independent receivers, and we record only the mean value. In this way the mean amplitude of the fluctuations is reduced by about a half.

If cosmic radio-frequency radiation at about 20 MHz is used for determining the additional absorption, the records thus obtained are free from fading. The radiation coming from the outside penetrates the absorbing *D*-layer only once and avoids reflection. But this method is much less sensitive, since it has to operate with a higher frequency and the absorption decreases nearly

proportionally to $1/f^2$. Records of cosmic radio-frequency radiation are especially good illustrations of the actual absorption variation in the case of major effects, where other methods will mostly fail because of complete fade-out.

Fig. 36 contains original records of cases of sudden rises in absorption. In the upper part here are records of effects of medium strength by means of the diversity method, below a stronger effect obtained by recording the cosmic radiofrequency radiation. The exactitude of the absorption variation derived from the records is sufficient for carrying out the following comparison.

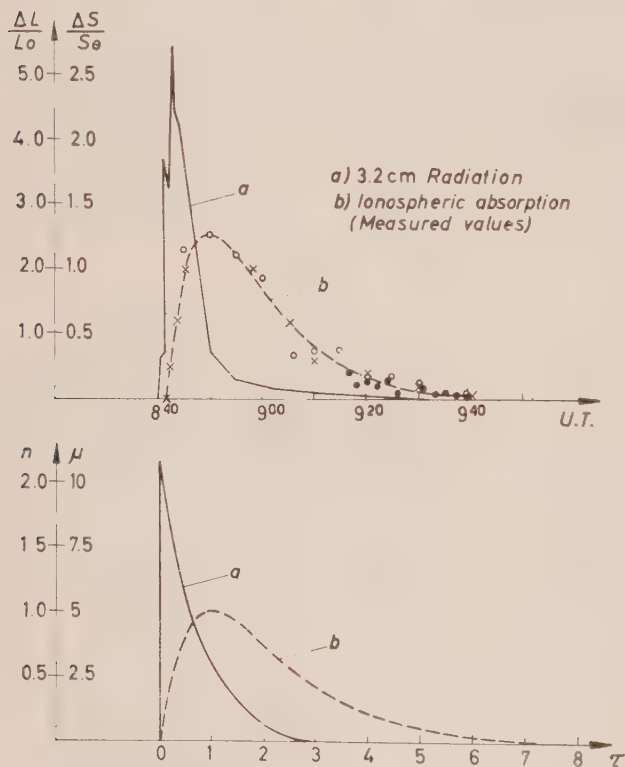


Fig. 37. - Comparison between the recorded 3.2 cm. radiation and the variation of the X-ray component derived from ionospheric absorption. Flare of 1958, June 5, 8^h 40^m U.T.

of the X-radiation was less high at the beginning, but had a longer slope. The variation of the radio emission is similar in this case too.

As already said, one may hardly expect to find any details, if, for instance, two radiation maxima follow each other within a few minutes (1 to 5 min) this radiation variation is smoothed out to such a degree that it becomes hardly

2'3. Comparison between the variation of the X-ray component derived from absorption and records of the centimetre radiation. - For a few examples I have determined the variation of the X-ray component from the absorption variation in an approximate manner. Fig. 37 contains the observed absorption variation and the recorded centimetre radiation; in the lower part we see the approximation of the absorption variation and the probable variation of the X-ray component derived from it. The similarity with the centimetre radiation is obvious.

Fig. 38 illustrates an absorption variation with a slower rise than Fig. 37. Accordingly the intensity

recognizable. Or it would be necessary to have absorption measurements of much higher exactitude.

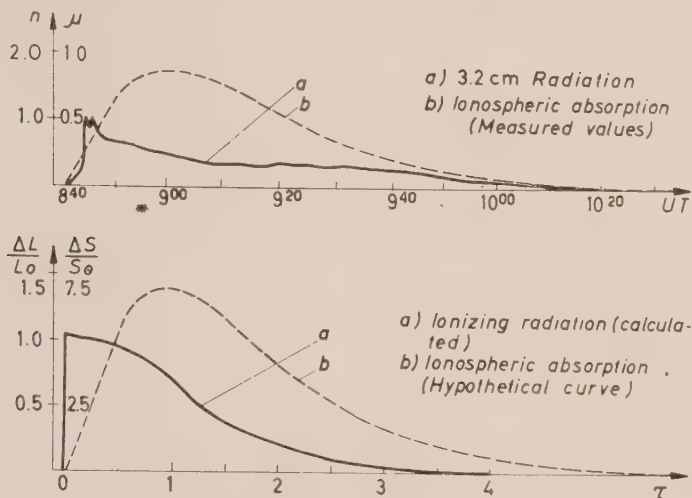


Fig. 38. — Comparison between the recorded 3.2 cm, radiation and the variation of the X-ray component derived from ionospheric absorption. Flare of 1957, December 14. 11^h 00^m U.T.

To conclude with, Fig. 39 shows another absorption variation with a very slow rise and fall. The process is so slow that it may be regarded as stationary so that the intensity variation of the X-radiation runs practically parallel to that of the absorption. The variation of the centimetre radiation corresponds to a burst of the «gradual-rise-and-fall» type. Also in this case, which is a special case of the above derivation, the variations of the ionizing radiation and the centimetre variation are similar.

The above method of comparing the cm radiation with the X-radiation

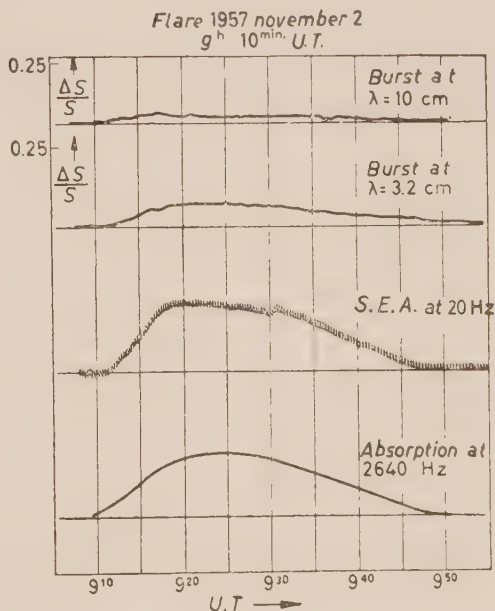


Fig. 39. — Burst of the «gradual-rise-and-fall» type compared with the variation of ionospheric absorption.

tion of flares has to be regarded only as a first attempt. Another investigation will have to be carried out concerning the law of recombination to be applied for the ionospheric *D*-layer; by means of the spectrum it will be further necessary to exclude from the cm radiation the percentage of radiation effected by an emission band.

Still the results of this first attempt seem to be satisfying enough to encourage further work in the same direction.

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Solar Radio Interferometry.

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1. -- Introduction.

Useful resolution of features on the sun's disk at radio frequencies requires apertures of linear dimensions of the order of 100 metres at centimetre wavelengths and some kilometres at metre wavelengths. Such resolution is beyond the scope of ordinary radio telescopes, and has led to the widespread application of interferometry.

We shall start this survey by considering the simplest application of interferometry. *viz.* the location in one dimension of discrete, isolated sources. Such « position finding » is relevant in the study of the intense transient sources which appear on the sun at metre wavelengths. Thence we shall proceed to show how first one-dimensional and then two-dimensional brightness distributions can be derived from interferometric observations.

2. -- The two-aerial interferometer.

Consider two aerials spaced a distance a apart and connected to a central receiving system through equal lengths of cable (Fig. 1). When plane waves whose electric field is given by $E \cos 2\pi(ft + (x/\lambda))$ arrive from a direction inclined at an angle θ to the normal plane bisecting the interferometer axis, the signals reaching the mixing point through the two aerials

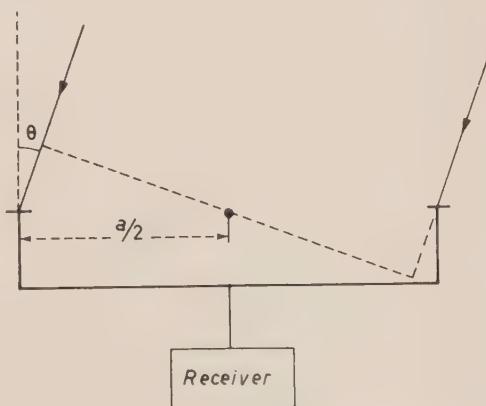


Fig. 1. -- The two-element interferometer.

traverse paths which differ by $a \sin \theta$, and so their voltages at the mixing point may be written

$$v_1 = E \cos 2\pi \left(ft + \frac{a \sin \theta}{2\lambda} \right) g_1(\theta),$$

$$v_2 = E \cos 2\pi \left(ft - \frac{a \sin \theta}{2\lambda} \right) g_2(\theta),$$

where $g_1(\theta)$, $g_2(\theta)$ designate the directional response of the aeralis. The voltages may be mixed in two ways:

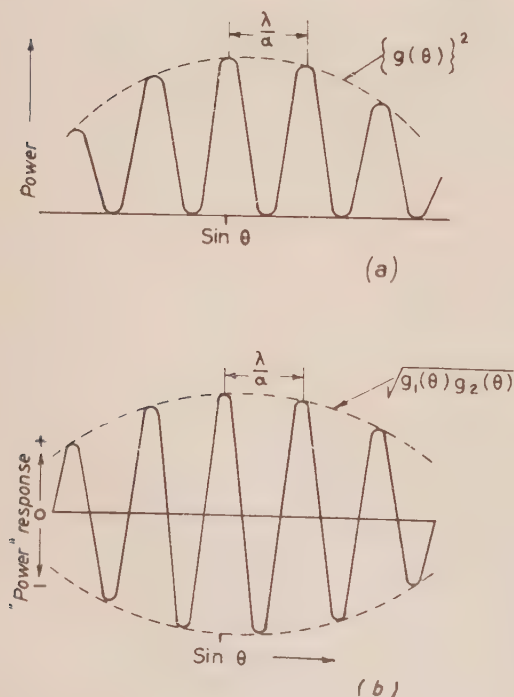
i) They may be *added* (e.g. using an ordinary T junction at the mixing point), whence in the case of interest ($g_1 = g_2 = g$) the power measured by the receiver is proportional to the time averages

$$(1) \quad \overline{(v_1 + v_2)^2} = 4E^2 \cos^2 2\pi ft \cos^2 \frac{\pi a \sin \theta}{\lambda} g^2(\theta) = E^2 \left(1 + \cos \frac{2\pi a \sin \theta}{\lambda} \right) g^2(\theta).$$

Alternatively,

ii) They may be *multiplied* (e.g. using a « phase-switched » receiver), whence the power is proportional to

$$(2) \quad v_1 v_2 = \frac{1}{2} E^2 g_1(\theta) g_2(\theta) \cos^2 \frac{2\pi a \sin \theta}{\lambda}.$$



The functions (1) and (2) are shown in Fig. 2, and represent the *aerial patterns* of the two systems. Either system can be used for locating isolated sources (for which purpose observations at a different spacing are usually needed to identify the correct lobe). Each system has advantages peculiar to itself. Thus adding interferometers can allow the angular size of the source to be estimated from the relative amplitude of maxima and minima, while the fixed zero line of multiplying

Fig. 2. - Aerial patterns of the two-element interferometer with a) the adding and b) the multiplying system.

systems is useful for eliminating unwanted deflections due to general background radiation and receiver noise. Other special applications of multiplying interferometers will be discussed later.

2.1. *The drift interferometer.* — The two-aerial interferometer or its equivalent was first applied by MCCREADY, PAWSEY and PAYNE-SCOTT [1] and by RYLE and VONBERG [2] to study the storm radiation from sunspots. The former used a system with one aerial and sea reflection analogous to the «Lloyd's mirror» experiment, while the latter used the normal two-aerial system which is analogous to Michelson's stellar interferometer. In both cases the interference pattern was generated by allowing the source to drift through

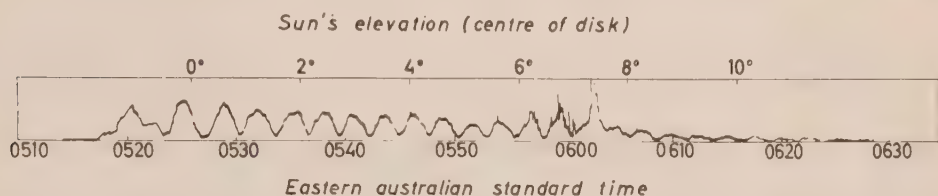


Fig. 3. — Interference pattern of a 200 MHz storm-centre on the sun recorded with a sea-reflection interferometer (MCCREADY, PAWSEY and PAYNE-SCOTT).

the aerial lobes. Fig. 3 shows an early record obtained thus by MCCREADY, PAWSEY and PAYNE-SCOTT who were able to demonstrate that the radio emission originated near sunspots.

2.2. *The swept-phase interferometer.* — For the study of short-lived bursts of radiation which may last only a few seconds, it is necessary to sweep the lobes of the aerial pattern by artificial means. LITTLE and PAYNE-SCOTT [3] accomplished this by mechanically sweeping the phase of signals in one arm of the system using a rotary phase-changer. They were thus able to scan the sun 25 times per second and so follow rapid temporal changes in position. By this means they demonstrated that sources of certain solar disturbances at 100 MHz moved rapidly across the disk of the sun.

2.3. *The swept-frequency interferometer.* — Recent investigations of the origin of solar bursts have demonstrated the need for positional data as a function of frequency as well as time. For this purpose a swept-frequency interferometer has been devised. Suppose that, in Fig. 1, an extra cable length l is inserted in one arm only of the interferometer, and that the receiver is capable of being swept rapidly in frequency over a considerable range. Then the record of power versus frequency generated by a broad-band distant source of angular co-ordinate θ will show a sinusoidal fringe pattern in which the maxima occur

at frequencies given by

$$f_n = n \frac{c}{l + a \sin \theta},$$

where n is an integer and c denotes the velocity of light. Hence the instrument can be used to measure the position co-ordinate θ effectively instantaneously at many frequencies. A detailed description of a swept-frequency interferometer for solar observations has been given by WILD and SHERIDAN [4], and results thus obtained form the basis of an investigation discussed in the author's companion article on Solar Radio Spectroscopy.

3. - The determination of a one-dimensional brightness distribution.

When a multiplying two-aerial interferometer is used to view an extended, complex brightness distribution near the zenith ($\theta \ll \pi$ throughout the distribution), it follows from a logical extension of equation (2) that the power recorded is proportional to

$$P\left(\theta, \frac{a}{\lambda}\right) = \int_{-\infty}^{\infty} B(\theta') \cos \frac{2\pi a(\theta - \theta')}{\lambda} d\theta',$$

where θ' defines a system of angular co-ordinates, fixed with respect to the source distribution, in the plane containing the interferometer axis, and $B(\theta')$ denotes the «one-dimensional brightness distribution» formed by line-integrating the actual (two-dimensional) distribution along lines normal to the interferometer axis. For simplicity we have ignored the slowly varying g -functions on the assumption that they do not vary appreciably across the source. Integration between infinite limits is justified when the source distribution is non-zero only over a limited range of θ' -values.

Introducing the *resolution*, r , of the interferometer defined by

$$r = \frac{a}{\lambda},$$

we obtain

$$(3) \quad P(\theta, r) = \int_{-\infty}^{\infty} B(\theta') \cos 2\pi r(\theta - \theta') d\theta'.$$

We now specify the brightness distribution in terms of its cosine and sine

spatial Fourier components, $\bar{B}_c(r)$ and $\bar{B}_s(r)$, which are given by

$$\bar{B}_c(r) = \int_{-\infty}^{\infty} B(\theta') \cos 2\pi r \theta' d\theta',$$

$$\bar{B}_s(r) = \int_{-\infty}^{\infty} B(\theta') \sin 2\pi r \theta' d\theta'.$$

Equation (3) then becomes

$$(4) \quad P(\theta, r) = \bar{B}_c(r) \cos (2\pi r \theta) + \bar{B}_s(r) \sin (2\pi r \theta).$$

Considered as a function of θ , this equation represents the pattern recorded as the fringes of the interferometer's aerial response are swept through the source distribution (whether by the earth's rotation or artificial means). *It consists of a pure sine wave whose amplitude and phase correspond to the amplitude and phase of the Fourier component of the source distribution with « frequency » r .*

In order to obtain sufficient information to derive the complete distribution, it is necessary to determine Fourier components over the complete range of r -values by taking interferometer records at many different spacings. If then we add the records together in the correct phase, the operation is represented by $\sum_r P(\theta, r)$, which is equivalent to the continuous integral $\int_{-\infty}^{\infty} P(\theta, r) dr$ if r -values are taken at sufficiently frequent intervals and over a sufficiently extended range. The result of this addition is then obtained by applying Fourier's integral theorem to equation (4), namely (since $B(\theta)$ is real)

$$\int_{-\infty}^{\infty} P(\theta, r) dr = B(\theta),$$

giving the desired brightness distribution. As an alternative to adding the records, one may plot the Fourier transforms $\bar{B}_c$ and $\bar{B}_s$ directly from the observation, and then perform an inverse transformation to obtain $B(\theta)$.

3.1. The effects of incomplete resolution (« aerial smoothing »). — To obtain a true one-dimensional brightness distribution in the most general case, we would need to extend the base-line of our interferometer to infinite lengths. In practice however we can usually ascribe to any brightness distribution a « finest structure »—that is to say we can assume its Fourier transform $\bar{B}(r)$

reduces to zero when r exceeds some value r_m . Under these conditions, we can derive the true distribution but must ensure the spacing is taken up to $a - \lambda r_m$. If this is not done the source is said to be incompletely resolved, and a distorted distribution is derived.

3'1.1. The equivalent aerial pattern. — Another way of looking at the problem of incomplete resolution is in terms of the « equivalent aerial pattern » of the multiply-spaced interferometer, *i.e.* the pattern which we would derive by the process of Section 3 when viewing a point source. In this case the brightness distribution has the form of a δ -function, and if situated at $\theta' = 0$, its Fourier transform is $\bar{B}_e(r) = \text{const}$, $\bar{B}_s(r) = 0$. Hence if the summation is taken over all r between 0 and r_0 , we obtain (by integrating (4)), a pattern proportional to

$$F(\theta) = \int_0^{r_0} \cos(2\pi r \theta) dr = \frac{\sin(2\pi r_0 \theta)}{2\pi r_0 \theta}.$$

This has the form of a central maximum of total angular width $1/r_0$, with gradually diminishing positive and negative swings on either side.

It is important to note that if we combine the records in such a way that different resolutions are given different weighting factors $W(r)$, then the equivalent aerial pattern becomes

$$(5) \quad F(\theta) = \int_{-\infty}^{\infty} W(r) \cos 2\pi r \theta dr.$$

Hence the equivalent aerial pattern is just the Fourier transform of the weighting factor $W(r)$, which we term the « spectrum » of the aerial system.

These instrumental effects can be expressed in a more general way by writing down the expression for the distribution $B'(\theta)$ derived by scanning the distribution $B(\theta')$ with an aerial of pattern $F(\theta)$, thus

$$B'(\theta) = \int_{-\infty}^{\infty} B(\theta') F(\theta - \theta') d\theta'.$$

Then applying the convolution theorem we obtain the result

$$\bar{B}'(r) = \bar{B}(r) \bar{F}(r) = \bar{B}(r) W(r),$$

viz. that the Fourier transform of the derived distribution is given by the product of the Fourier transform of the true distribution and the spectrum of

the aerial. The last equation, which can be generalized for two dimensions, is the analogue of a well-known theorem in optics relating the properties of the image to those of the object and instrument. Its applicability to radio interferometer was recognized by BRACEWELL and ROBERTS [5] and by ARSAC [6].

3.2. *Applications to the quiet sun.* — The Fourier method of deriving a radio brightness distribution was suggested by MCCREADY, PAWSEY and PAYNE-SCOTT [1], and first applied by STANIER [7] to obtain a one-dimensional brightness distribution of the quiet sun at a frequency of 500 MHz. By assuming circular symmetry, STANIER proceeded to derive a radial distribution of brightness. A surprising feature of Stanier's distribution, which was obtained during a sunspot maximum phase was the complete absence of limb-brightening effects that were predicted by existing theories. The experiment was repeated in two dimensions (see Section 4) by O'BRIEN at the sunspot minimum phase, and although a suggestion of limb brightening was present, its form showed none of the predicted *sharp* features *beyond* the limb. O'Brien's

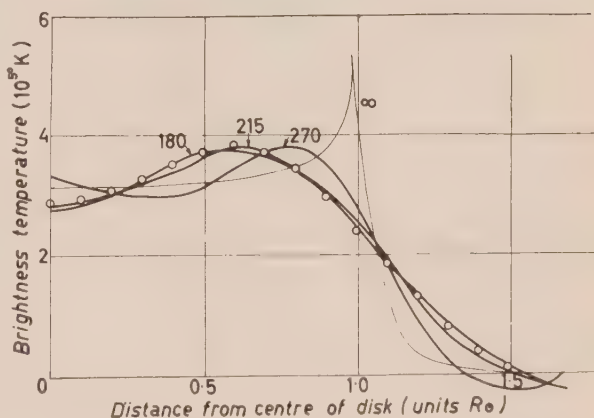


Fig. 4. — Comparing a theoretical and an observed radial distribution, and showing the effects of incomplete resolution upon the theoretical distribution (SMERD, unpublished).

radial distribution (equatorial scan) is compared in Fig. 4 with a typical theoretical distribution derived by SMERD. While this disagreement could be due to the use of an incorrect theoretical model, it has been pointed out by SMERD (private communication) that the effects of incomplete resolution could be responsible: the maximum resolution at which O'BRIEN obtained a finite response was $r_0 \approx 215$, and the curve marked «215» in Fig. 4 shows the approximate effect on Smerd's distribution of disregarding Fourier components of greater resolution. The agreement with the observed distribution is striking.

3.3. *Multiple interferometers.* — The virtues of the Fourier method of deriving a brightness distribution lie in the extreme simplicity of the equipment required and its general flexibility. However it suffers from severe disadvantages in the complexity of the analysis and the time required to carry it out,

which forbids the study of transitory features. These difficulties may be overcome with an instrument which measures all the desired Fourier components simultaneously, that is to say which scans the source distribution with a thin, fan-shaped beam. One of the most successful instruments of this kind is the *grating interferometer* (analogous to the diffraction grating in optics) introduced by CHRISTIANSEN in 1953.

3'3.1. The grating interferometer. — CHRISTIANSEN [8] used 32 aerial elements disposed along a straight line with equal spacing, a , between each

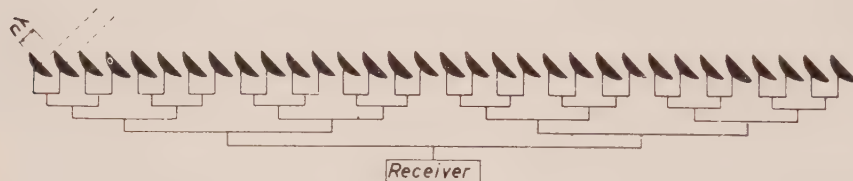


Fig. 5a. — Christiansen's grating interferometer: the aerial arrangement.

element. The elements are connected by equal lengths of cable to a common receiver as shown in Fig. 5a. To determine the aerial pattern $f(\theta)$ we first

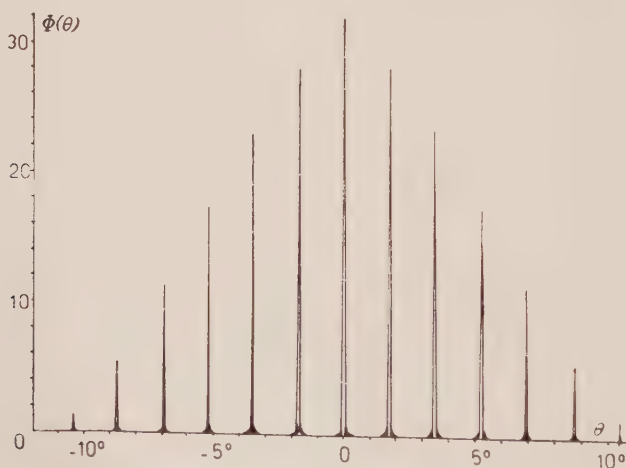


Fig. 5b. — Christiansen's grating interferometer: the aerial pattern.

calculate its spectrum, $W(r)$. We are now dealing with a combination of *adding* interferometers, and inspection of Fig. 5a, shows that, in relative units,

$$W(0) = 32, \quad W\left(\frac{a}{\lambda}\right) = 31, \quad W\left(\frac{2a}{\lambda}\right) = 30 \dots W\left(\frac{na}{\lambda}\right) = 32 - n.$$

Hence, applying equation (5) in summation form,

$$F(0) = \sum_{n=0}^{32} (32 - n) \cos \left(\frac{2\pi n a \theta}{\lambda} \right) = \text{const} \frac{\sin^2 \{32\pi(a/\lambda)\theta\}}{32 \sin^2 \{\pi(a/\lambda)\theta\}}.$$

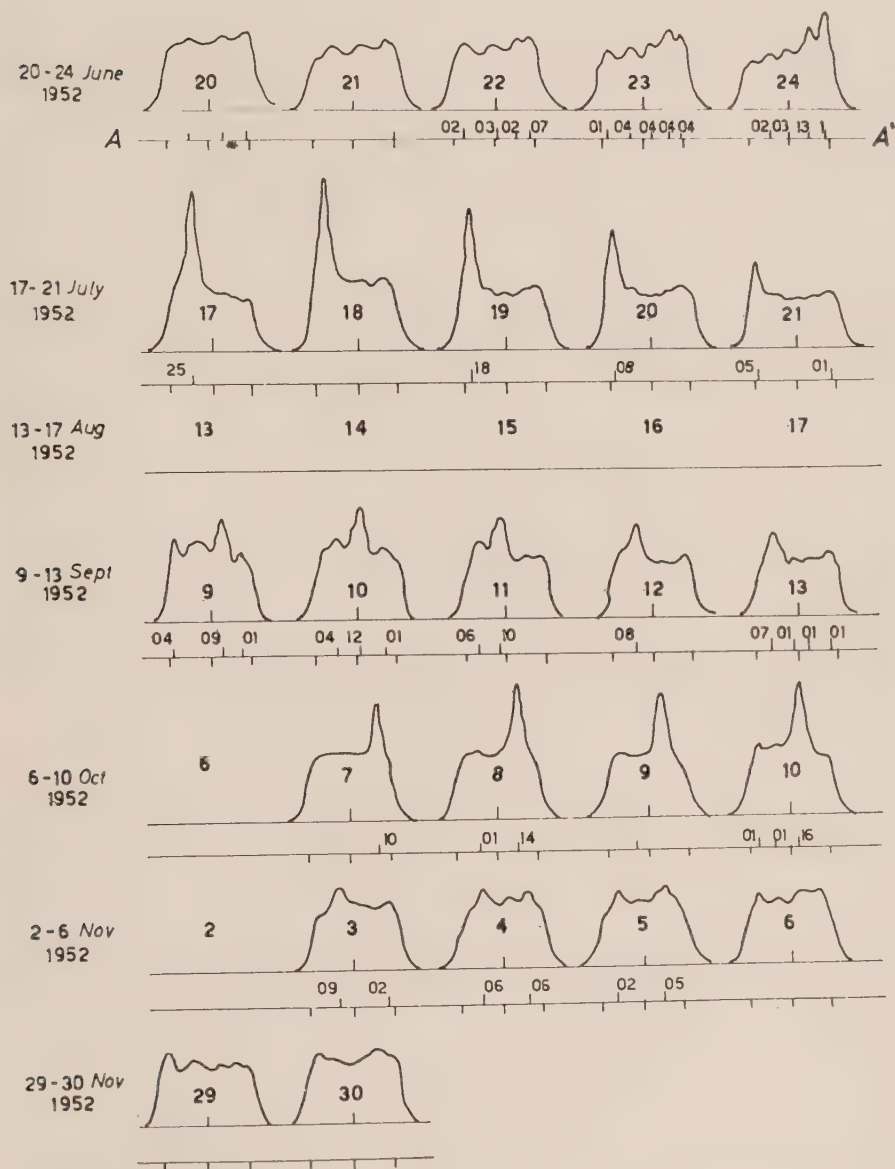


Fig. 5a. - Christiansen's grating interferometer: strip scan of the sun $\lambda = 0.21$ m showing resolution of quiet sun and active centres.

(This is the aerial pattern for small values of θ . It can be shown that the general case is given by replacing θ by $\sin \theta$ in this equation.) The pattern (Fig. 5b) shows a series of well-separated fan-shaped beams, and the analogy with the optical diffraction grating is clear. As shown in the figure, the fringe pattern is modulated by the envelope defining the aerial pattern of one individual element.

In Christiansen's aerial, $a = 7.5$ m and $\lambda = 0.21$ m, giving a fringe width ($\sim \lambda/32a$) of $3'$ arc—i.e. one tenth the diameter of the optical disk—and a fringe spacing ($\sim \lambda/a$) of 1.7° —i.e. 3.4 solar diameters. Thus as the sun drifts through successive fringes a series of separated one-dimensional scans are recorded directly (Fig. 5c). By this means individual active centres on the sun were resolved and these appeared above the general level of the quiet sun.

3.3.2. The broadside array — A limiting case of the grating interferometer is obtained by reducing the spacing between adjacent elements to the extent that only one fringe remains in the general envelope of the aerial pattern. Such a « broadside array » in the form of a long, slotted waveguide was successfully used by COVINGTON [9] to study solar radiation at $\lambda = 10$ cm.

3.3.3. Irregular gratings. — The grating with equal spacing clearly contains considerable redundancy in its spectral content, exemplified in Christiansen's instrument by the fact that information on the Fourier component of spacing a/λ is obtained from no less than 31 different combinations of aerial elements. Such redundancy can in principle be eliminated or reduced by omitting certain elements. One special arrangement, proposed by ARSAC [6], is the following (in which aerals are represented by crosses and blanks by dots):



$\times \times \dots \times \times$

This contains just one component of each spacing between 1 and 6, but the aerial pattern contains large side lobes. Solutions for larger arrays with this special feature cannot be found, and compromise solutions give aerial patterns of doubtful values (see ARSAC [6]). In general it appears that economy in the number of aerial elements can only be obtained at the expense of desirable beam shapes. For this reason the regular grating has been widely adopted.

4. — The determination of a two-dimensional brightness distribution.

The ultimate aim of the interferometric technique is to register an actual two-dimensional picture of an object in the sky. This is a major challenge, but one which has been tackled before, on a very different scale, in the science

of crystallography. While in some cases radio astronomy has borrowed its techniques from this science, in others entirely new methods have been developed. Two broad solutions of this problem have been found: these will be referred to as the «radial» and «rectangular» solutions.

4.1. *The radial solution.* — This solution which was adapted from crystallography and applied by O'BRIEN [10], allows us to derive a two-dimensional distribution from a series of one-dimensional strip scans taken at many different orientations. The strip scan in any one orientation can be obtained either by a single scan with the fan beam of a grating interferometer or broadside array, or by many scans at different spacings with a two-aerial interferometer using the methods discussed in Section 3. In the formulation given below, fan-beam scanning will be envisaged. Let the brightness distribution under observation be given by $B(x, y)$, where x and y represent a system of rectangular co-ordinates in the approximately plane surface over a small part of the celestial sphere. The method depends on 1) determining the two-dimensional Fourier transform of $B(x, y)$, viz.

$$(6a) \quad \bar{B}(\xi, \eta) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} B(x, y) \exp [2\pi i(x\xi + y\eta)] dx dy,$$

and then 2) performing the inverse transformation to recover

$$(6b) \quad B(x, y) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \bar{B}(\xi, \eta) \exp [-2\pi i(x\xi + y\eta)] d\xi d\eta.$$

To accomplish stage 1), we first use our fan-beam instrument to obtain the strip-scan parallel to the x axis; this is given by

$$\int_{-\infty}^{\infty} B(x, y) dy.$$

We then calculate the (one-dimensional) Fourier transform of this recorded function. This is

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} B(x, y) \exp [2\pi i\xi x] dx dy,$$

which, by inspection of equation (6a), is seen to be just

$$\bar{B}(\xi, 0).$$

Thus we have determined $\bar{B}(\xi, \eta)$ for all points along the ξ -axis. We can similarly obtain points along any other axis from scans in the corresponding direction in the (x, y) plane. Thus from a sufficiently large number of scans we can draw a contour map of $\bar{B}(\xi, \eta)$.

To accomplish stage 2) we adopt the identical procedure to transform $\bar{B}(\xi, \eta)$ back to $B(x, y)$ —i.e. by plotting one-dimensional Fourier transforms of strip scans in many orientations—, but now the «strip-scanning» is performed by graphical integration instead of aerial scanning.

In this derivation we have treated the case of infinite resolution. The smoothing effects which result from finite resolution are similar to those previously discussed for the case of one dimension, and are discussed in detail in a paper by SMERD and WILD [11]. The above method is most straightforward for a source distribution possessing radial symmetry, in which case $\bar{B}(\xi, \eta)$ is real. However unsymmetrical distributions present no fundamental difficulty since the real and imaginary parts of $\bar{B}(\xi, \eta)$ can be plotted and treated separately, and subsequently combined.

4.1.1. Application to the quiet sun. — O'Brien's original application [10] was to the quiet-sun distribution at $\lambda = 1.4$ m, and later [12] at $\lambda = 0.6$ m using a two-aerial interferometer. The method was also used by CHRISTIANSEN and WARBURTON [13] using grating interferometers for the quiet

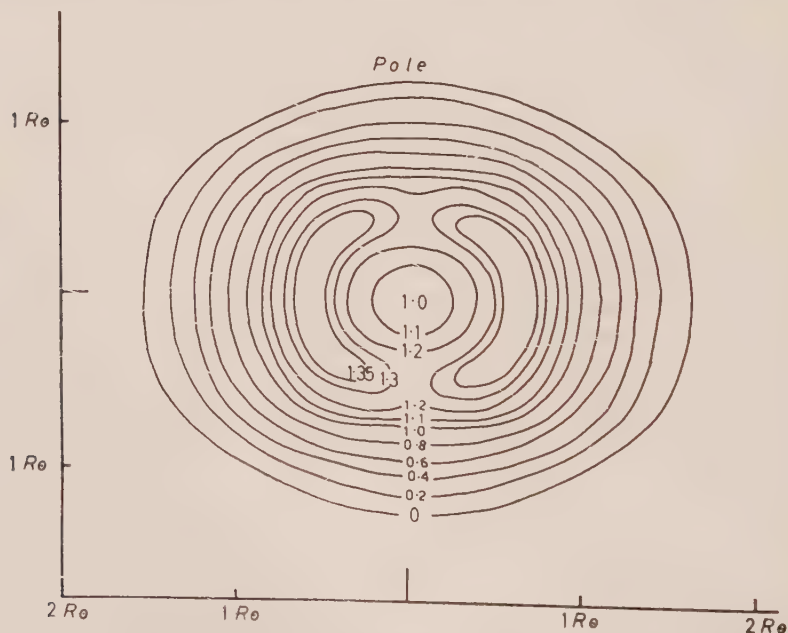


Fig. 6a. — Quiet sun distributions derived by O'BRIEN and TANDBERG-HANSEN at $\lambda = 0.6$ m.

sun at $\lambda = 0.21$ m. These observations provided the first direct evidence of limb brightening (see Fig. 6a and b).

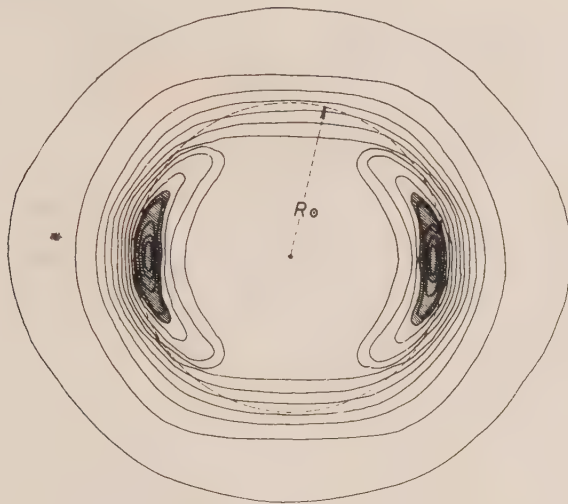


Fig. 6b. — Quiet sun distribution derived by CHRISTIANSEN and WARBURTON at $\lambda = 0.21$ m.

4.2. *The rectangular solution.* — The rectangular solution made its appearance in radio astronomy in an instrumentally advanced form with the «Mills Cross» aerial [14], which consists of two linear arrays forming the two arms of a cross. The aerial patterns of the two arms are mutually-perpendicular fan beams, and when the e.m.f.'s induced in the two arms are *multiplied* together, the final beam consists of a pencil beam whose angular size corresponds to the overlapping portion of the two fan beams. With such an instrument a brightness distribution can be recorded directly by two-dimensional scanning.

In its most elementary form [15], the rectangular solution requires two adding interferometers (resolution ξ and η , say) which are arranged with a common central point along two perpendicular base lines, and the e.m.f.'s delivered by the two interferometers are multiplied together. By sweeping the phase (x' , y') of each of the two interferometers—one slowly and the other rapidly—a record is generated of the two-dimensional Fourier component

$$\bar{B}(\xi, \eta) \exp [-2\pi i(x'\xi + y'\eta)] .$$

Hence it follows from equation (6b) that if the same procedure is repeated for a complete range of combinations of resolutions ξ and η , and if all the recorded two dimensional patterns are superimposed and added, the result will yield the required brightness distribution $B(x', y')$.

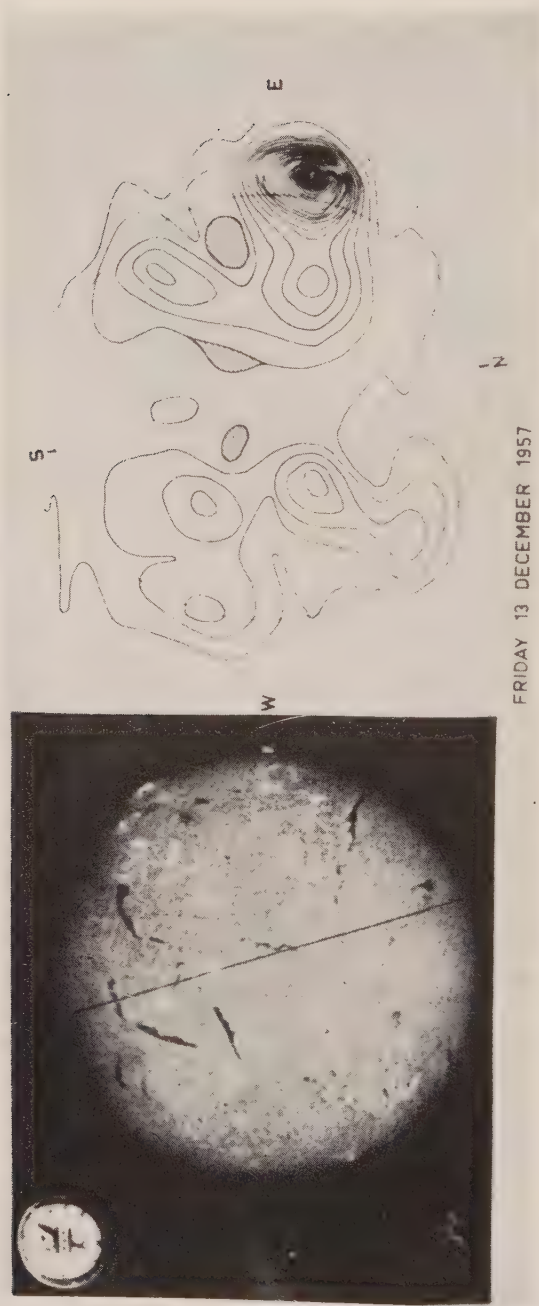


Fig. 7. - Two-dimensional brightness distribution of the sun at $\lambda = 0.21$ m obtained by scanning with Christiansen's crossed grating.

By this method we are effectively synthesizing a Mills Cross with the use of 4 aerial elements, just as by O'Brien's radial method we effectively synthesize a circular aperture with the use of 2.

4.2.1. Christiansen's crossed grating. — In solar studies the rectangular solution has found application in Christiansen's [16] combination of the grating interferometer and the Mills-Cross principle. The aerial pattern of the «crossed grating» consists of the overlapping portions of two mutually-perpendicular sets of equally-spaced fan beams—*i.e.* a series of widely-spaced, fine pencil-beams arrayed as a matrix. In Christiansen's design the parameters of each grating are similar to those given in Section 3.3; the spacing between beams is again greater than the Sun's radio disk, so that the latter can be scanned by one beam at a time. The angular diameter of the beam is about 3' arc, and phase-shifting arrangements are incorporated to allow a complete picture of the sun to be obtained in about $\frac{1}{2}$ hour. This allows the study not only of the quiet sun, but also of certain classes of transitory phenomena such as the slowly-varying centres of activity and the more durable of the outbursts associated with flares (see Fig. 7).

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Solar Radio Spectroscopy.

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1. - Introduction.

This survey deals with the spectrum of the bursts, outbursts and storms of radio emission which take place on the Sun at metre wavelengths, notably at the time of flares. As with their optical counterpart, the results give information on the regions of the solar atmosphere in which the disturbances take place, and of the disturbances themselves; but unlike the optical radiation, which is caused by quantum transitions within atoms, the radio emission originates in classical processes involving the oscillatory motion of «free» electrons. Also the radio wavelengths originate substantially in the outer parts of the solar corona which is transparent to optical wavelengths; hence the information gained is independent of, yet complementary to, that available optically.

1.1. *The radio spectrograph.* - The radio spectrograph consists of a tunable receiver, in which a narrow band of reception is swept over a broad frequency range. Most of the spectra illustrated here were taken with the Dapto (Sydney) spectrograph [1], which now covers the range $(25 \div 210)$ MHz. In this case the frequency is mechanically swept over its entire range once every $\frac{1}{2}$ second, and the *dynamic spectra* are displayed on a cathode-ray tube and recorded photographically as a series of intensity-modulated traces which register intensity as a brightening in the frequency-time plane (see accompanying figures). The spectrum in Fig. 1 was taken at the University of Michigan whose spectrograph covers the range $(100 \div 600)$ MHz.

2. - Classification of dynamic spectra.

Recorded spectra show a wide variety of patterns, but examination of data over several years suggests that the great majority fall in 5 classes described below. The first 3 types belong to the original classification of WILD and

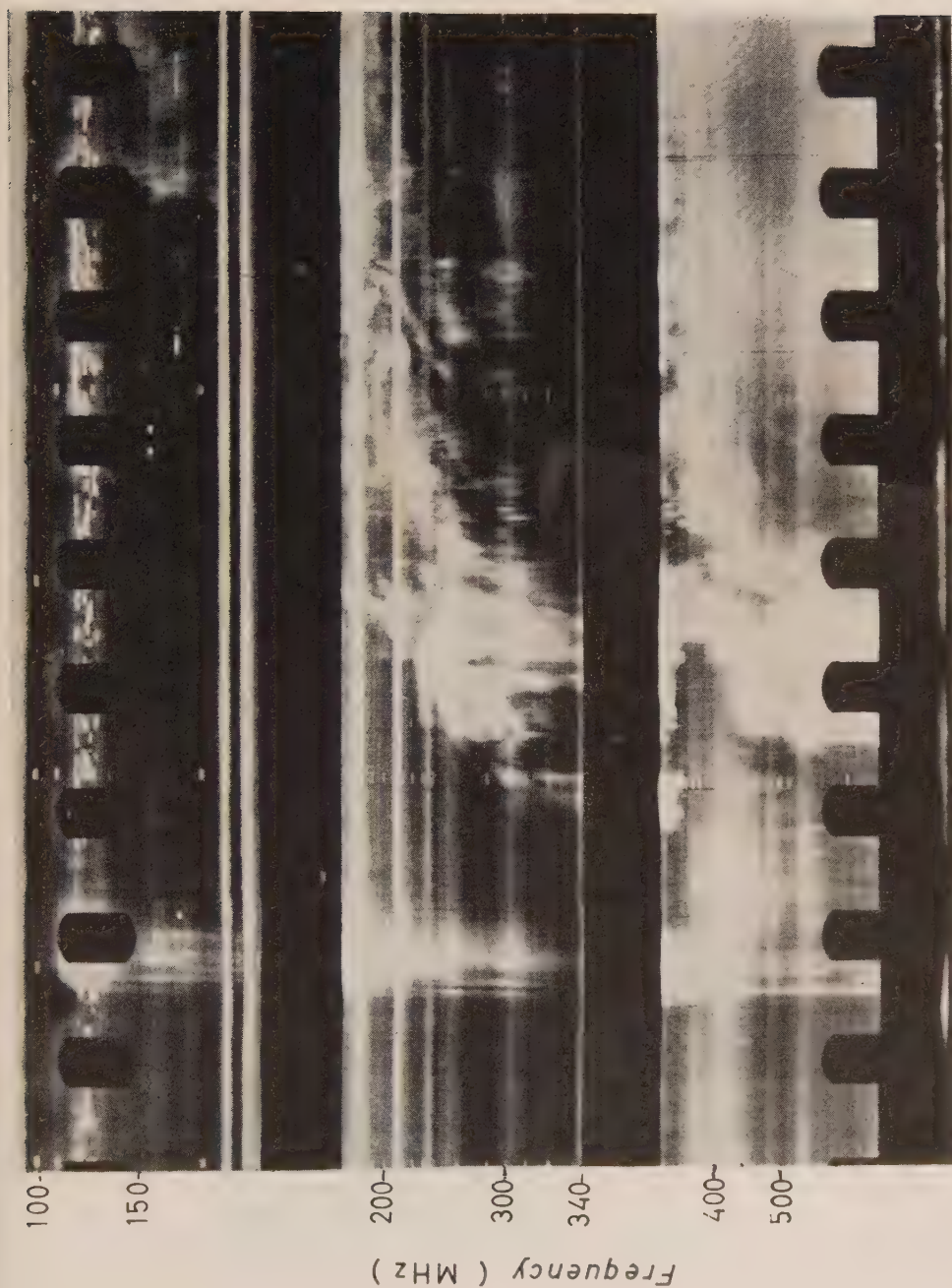


Fig. 1. The start of a type IV burst following a type II. (Haddock).

McCREADY [2], the fourth was distinguished by BOISCHOT [3] from observations with the Nançay interferometer, and the fifth has recently been described by WILD, SHERIDAN and NEYLAN [4].

Type I « storm » bursts [5] which occur in 100's or 1000's during storms, are characterized by their narrow bandwidth (a few MHz), short duration ($\approx$ seconds), and strongly circular polarization. They often appear above a quasi-stable background-continuum similarly polarized.

Type II « slow drift » bursts [6, 1, 7] (Fig. 2) are outstanding events lasting ~ 10 minutes which occur in the postmaximum phase of certain large flares and are characterized by a «slow» systematic drift in spectral features from high to low frequencies at the rate of ~ 0.2 MHz per second. Polarization is usually random.

Type III «fast drift» [8-10, 4] (Fig. 3) are common events lasting ~ 10 s which occur in groups especially near the start of flares and micro-flares, and are characterized by a «fast» drift in the frequency of maximum intensity from high to low frequencies at the rate of ~ 20 MHz per second. Polarization may be random, or partially circular or elliptical.

Type IV « long continuum » bursts [3, 11-13] (Fig. 1) are rare events lasting hours which start late in the life of certain

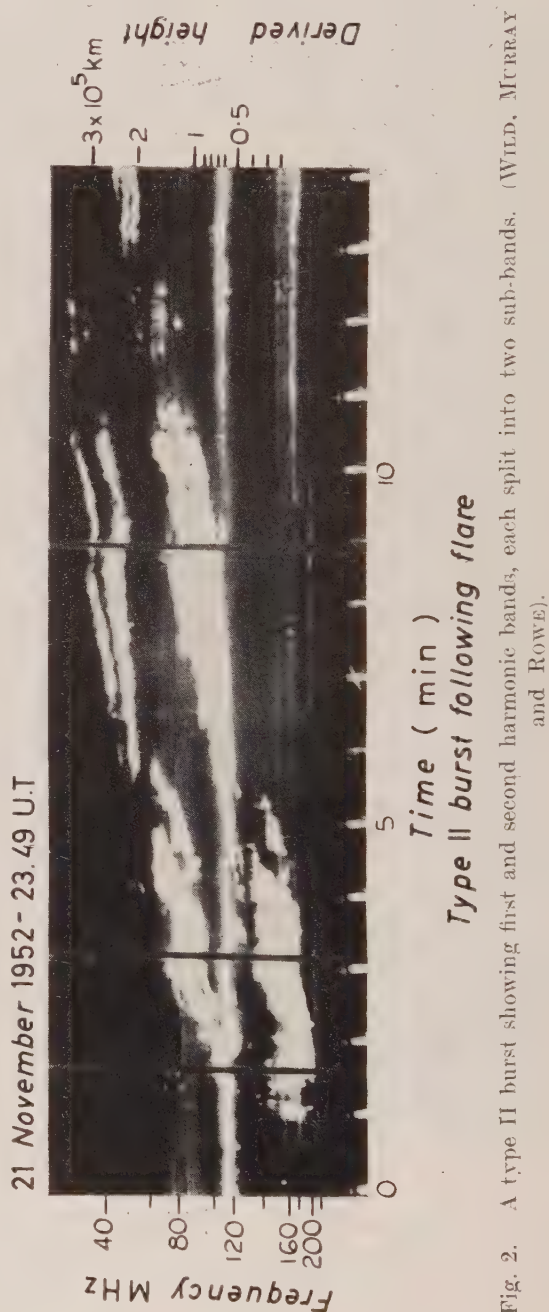
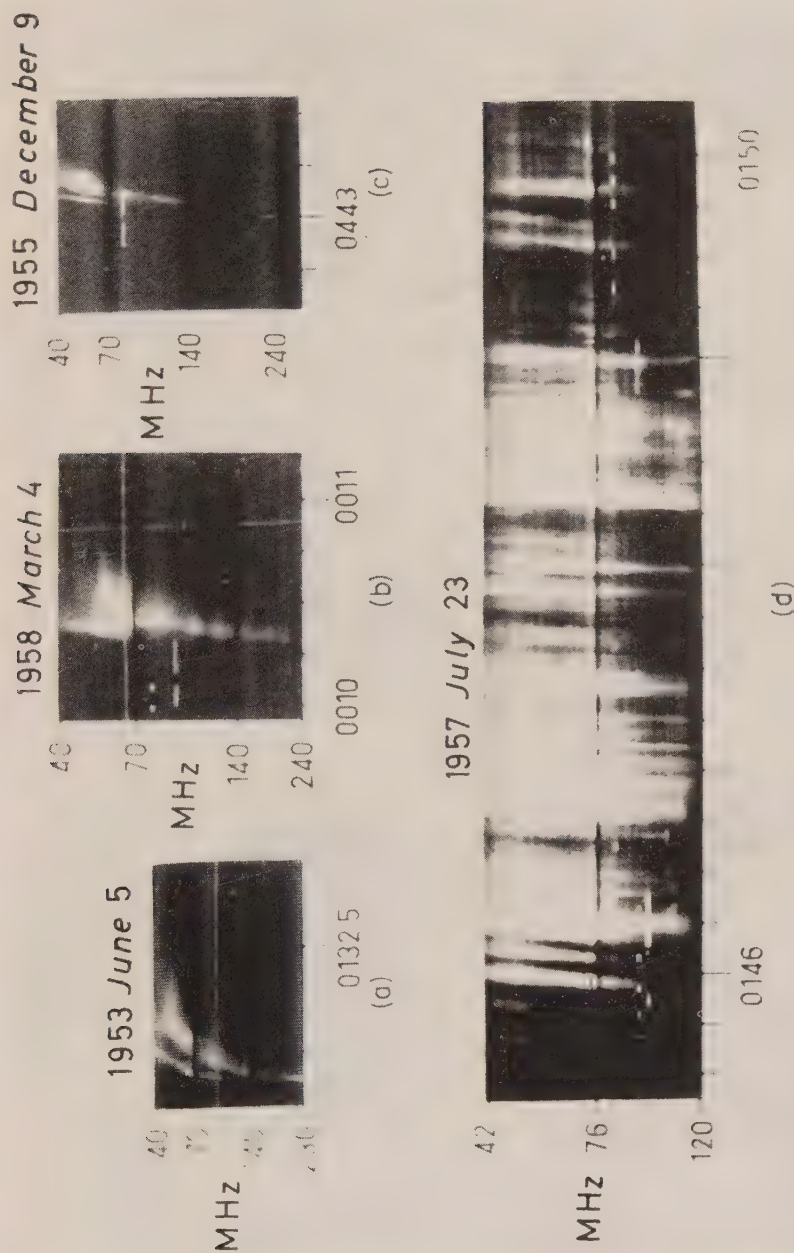


Fig. 2.



Universal time

Fig. 3. Type III bursts, showing individual events with harmonic structure (above), and a typical large group (below). (WILD, SMITHMAN and NEELAN).

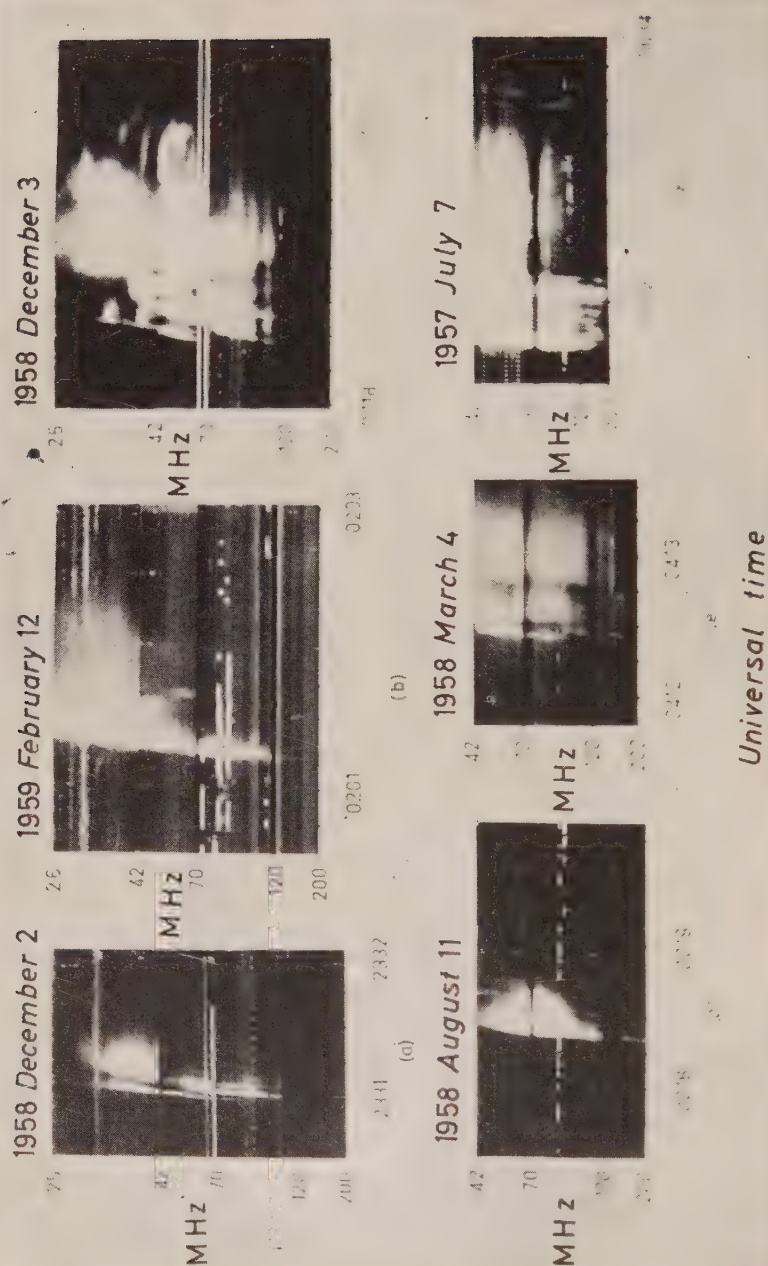


Fig. 4. Type III bursts which are accompanied by type V bursts. (WILD, SHERIDAN, and NEYLAN).

large flares following a type II burst. Their spectrum shows a broad-band, mainly featureless, continuum. Polarization is circular.

Type V «short continuum» bursts [4] (Fig. 4) are events lasting ~ 1 minute which immediately follow certain type III bursts. Their spectrum is a featureless continuum. Polarization may be elliptical.

2'1. *Variations.* – While the above classification covers nearly all phenomena, the following variations and unclassified types are worthy of special mention:

The inverted U (MAXWELL [14]): a variety of type III spectrum in which the frequency drift starts normally, becomes retarded and then completely reverses, causing the dynamic spectrum to resemble an inverted U (examples can be recognized in Fig. 4c).

The reverse-drift pairs (ROBERTS [15]): an intriguing phenomenon observed at low frequencies (< 50 MHz) in which a short sharp feature with «reverse» (*i.e.* abnormal) frequency drift appears and is followed 1-2 seconds later by a similar feature. These sometimes occur as a structural feature within type III bursts, but more often on their own.

«Feather» structure in storms (MAXWELL [12]): Certain storms (tentatively regarded as a variety of type I) show a rapid sequence of very brief (< 1 s), *broad-band* bursts giving rise to a feathered appearance in the dynamic spectrum.

2'2. *Harmonics and split-bands* [1, 7]. – About 50% of type II bursts and a few per cent of type III bursts show duplication of their spectral features at about twice the frequency, indicating that the source radiates at a fundamental frequency and its second harmonic. The search for higher harmonics has been largely fruitless, though occasional suggestions of their existence have been reported.

Each of the two harmonic bands in some type II bursts sometimes show a splitting of finer structure, most commonly into two, but occasionally more, sub-bands.

2'3. *Relation with optical flares.* – Table I gives an indication of the probability of radio bursts of different spectral types occurring at the same time as (and presumably associated with) flares of different importance. It is based on available data taken from papers by LOUGHHEAD, ROBERTS and McCABE [10], ROBERTS [7] and MCLEAN [16]. It shows that with small flares, radio events are confined almost entirely to type III bursts, with or without their type V

TABLE I. - *Approximate probability (per cent) of flares of different importance producing the first and second phase of radio outbursts.*

Flare importance	1 ---	1	2	3
First phase (type III)	20-25	≥ 50	?	?
Second phase (type II)	0	2	7	31

Note: The probability of a type II burst being followed by a type IV burst is estimated to be $(10 \div 20)$ per cent. The probability of a type IV burst occurring with a class 3 flare is much (~ 30 times) greater than that with a class 2 flare.

accompaniment, while large flares may produce a type II burst and occasionally (especially with exceptional flares) a type IV burst.

In some major disturbances, all phases of the radio-flare event are represented

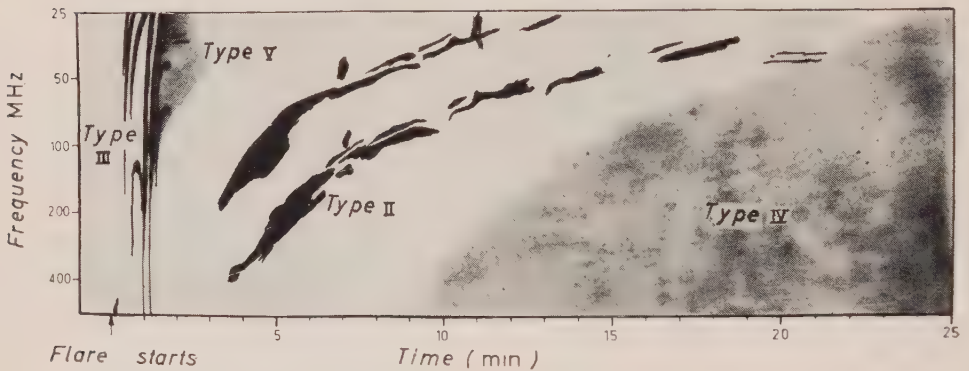


Fig. 5. - Idealized dynamic spectrum of a complete radio event. The type IV burst continues for a period of hours.

and such compound bursts nicely illustrate the time relationships between the optical and radio phenomena. An idealized sketch of a compound burst is shown in Fig. 5. The type III and V event occurs at the initial sudden expansion of the flare (see GIOVANELLI [17]) and a few minutes later the type II event starts; this is followed by, or merges into, the start of the type IV burst which continues for hours.

We now proceed to discuss current interpretations of the first and second phases of the compound flare event.

3. - Interpretation of type III bursts [8, 9, 4].

The existence of harmonics in type III bursts indicates that the emission is generated by electrons oscillating at a proper frequency. In the solar atmosphere the only known characteristic frequencies capable of continuous variation

are the *plasma frequency* ($f_p = e\sqrt{N/m\pi} = 9\sqrt{N}(\text{cm}^{-3}) \text{ kHz}$) and the *gyro frequency* ($f_H = eH/2\pi mc = 2.8 H (\text{gauss}) \text{ MHz}$). Considerations of the propagation of radio waves in an ionized medium show that the gyro frequency is unable to escape from a solar source because it encounters barriers of high attenuation or reflection in its outward path. This argument has led to wide acceptance of the view that type III (like type II) bursts originate in plasma oscillations. The adoption of the *plasma hypothesis* leads, as will be shown, to a consistent physical picture of the origin of the burst, and the predictions which have recently been verified experimentally.

According to the *plasma hypothesis*, the systematic frequency drift in type III bursts is interpreted as a rapid outward motion of a disturbance which excites plasma oscillations in the surrounding coronal gas: the greater the height of the disturbance, the lower the electron density surrounding it, and hence the lower the frequency emitted. Knowledge of the electron density as a function of height therefore allows us to derive the radial component of the velocity of the source. Until recently it was customary to assume one of the standard optical models of electron density (*e.g.* those due to ALLEN and VAN DE HULST) and these gave velocities in the range $0.1c$ to $0.3c$. Such velocities were far in excess of anything known from optical observations, and their verification by direct means became a matter of prime importance.

3.1. Verification of the plasma hypothesis by interferometry. — The plasma hypothesis predicts that when a type III disturbance is ejected quasi-radially from the limb of the Sun, different frequencies should arrive from different

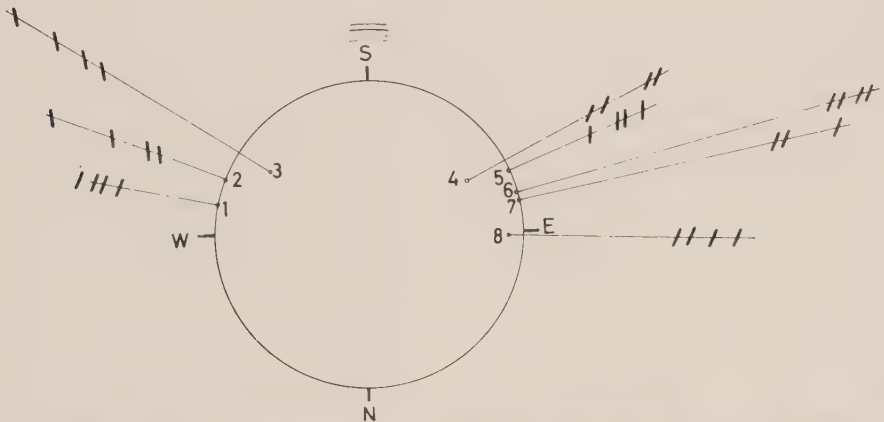


Fig. 6. Radio positions (black strips) of type III bursts associated with 8 limb flares (numbered dots). Proceeding radially outwards, the 4 positions associated with each event refer to the 4 frequencies 60, 55, 50, 45 MHz in that order. The thin arcs above the disk show the plasma levels of these frequencies when a standard model of the corona is assumed.

heights in the solar atmosphere, the lower frequencies originating at greater heights. This was recently confirmed by WILD, SHERIDAN and NEYLAN [4] using a swept-frequency interferometer (see companion article on Solar Radio Interferometry). The predicted effect is clearly evident in Fig. 6 which shows the positions at 4 frequencies of type III bursts ejected from 8 limb flares.

From a statistical analysis of about 100 bursts, the regions of origin were found to be at much greater heights than expected from the application of conventional solar models of electron density. Indeed the model required to fit the observations needed electron densities to be increased by a factor of about 10. However the required model agreed closely with that deduced optically for typical coronal streamers and it was suggested that the type III disturbances travel out along coronal streamers. A similar conclusion was reached by SHAIN [18] from observations at a much lower frequency (19.7 MHz).

3.2. *The velocity of type III disturbances* [4]. — The wider separation of plasma levels indicated by the interferometer observations leads to a substantial revision in the estimates of the radial components of velocity of type III disturbances. A revised velocity distribution is shown in Fig. 7. (Two slightly different distributions are shown based on different assumptions regarding the relative time of travel of different frequencies in an ionized medium.) The

mean velocity is seen to be $\sim \frac{1}{2} c$, and a significant feature of the distribution is the sharp low-velocity cut-off at $0.2 c$. The significance of these high velocities will be considered later.

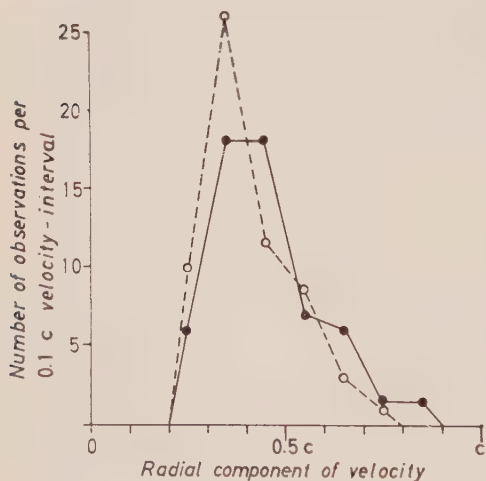


Fig. 7. — Distribution of the radial components of velocities of type III bursts, derived from combined observations with a spectrograph and interferometer. In that shown by the full line allowance has been made for dispersion in the propagation of different frequencies. The effect of neglecting this correction is shown by the dotted line. (WILD, SHERIDAN and NEYLAN).

4. — Interpretation of type V bursts [4].

Type V bursts lack the features (discrete bands, harmonics, frequency drift etc.) indicative of plasma emission, and it has been suggested that synchrotron radiation from electrons spiralling in a magnetic field provides a

much more likely mechanism. (This mechanism had previously been suggested by BOISCHOT [3] to explain type IV bursts; see Section 6).

Synchrotron radiation is due to high harmonics of the electron gyro frequency generated by spiralling electrons travelling at relativistic velocities. The frequency of maximum intensity is given approximately by

$$f_c = 16 BE^2 \sin \alpha \text{ MHz},$$

where B denotes the magnetic field (gauss), E the electron energy (MeV) and α the angle of pitch of the spiral. Assuming the radiation to be emitted in an effective bandwidth of $f_c/2$ and neglecting self-absorption, the flux density at the earth due to n electrons is found to

$$S = 2.7 \cdot 10^{-52} n B \sin \alpha \text{ W/m}^2 \text{ Hz}.$$

For the upper regions of the solar corona we take $B < 1.5$ G. Type V bursts are received mainly at frequencies < 100 MHz and their maximum flux density is $\sim 10^{-18}$ W/m² Hz. Substituting these values in the above equations we find that intense type V bursts require at least 10^{33} electrons with energies of 2 MeV or greater. However, present evidence indicates that the emitting regions attain large angular sizes (linear dimensions $\sim 5 \cdot 10^5$ km), and this total number of electrons requires densities not greater than 30 per cubic centimeter, *i.e.* very much less than the total electron density in the surrounding solar corona. The synchrotron hypothesis is therefore acceptable from this point of view.

4.1. *The nature of the disturbance producing the combined III-V event* [4]. — Our interpretation of type V bursts requires the temporary existence high in the corona (*i.e.* above the innermost level of escape, which is just the plasma level) of relativistic electrons with energies in the MeV range. Since these electrons must surely have originated at lower levels near the seat of the flare and since the type V burst occurs at the start of the flare, it seems highly probable that the electrons are transported to the upper coronal regions with very great rapidity. It is therefore extremely tempting to identify this act of transportation of the type V electrons with the source of the type III bursts. The fact that the majority of type III disturbances are rather slower than the speed (approximately c) of MeV electrons is to be expected if the electrons travel along lines of magnetic force in a spiral path. Such electrons would be practically unimpeded by collisions with coronal electrons and protons.

It is therefore concluded from the radio evidence that the formation of many, perhaps most, flares is accompanied by the ejection of a stream of particles containing not less than $3 \cdot 10^{33}$ electrons with energies ≥ 2 MeV; that

the particles follow a spiral path along lines of magnetic force delineating coronal streamers; that, by some process not fully understood, they excite plasma oscillations in the surrounding coronal gas, causing the type III burst to be emitted; and that under favourable conditions the electrons themselves radiate synchrotron radiation, causing the type V burst. In most cases the corpuscular disturbance appears to escape into interplanetary space, while in others it is guided back to the sun along a line of force (producing in this case an inverted U burst). When escape is complete, we are left with a source of interplanetary electrons, and it is an interesting matter for conjecture whether these may be responsible for the corpuscular radiation round the earth which has recently been discovered with satellites.

5. - Interpretation of type II bursts [6, 1, 7].

The second phase (type II and type IV bursts), of the complete solar radio event whose appearance is restricted mainly to times of large optical flares, has features in common with the first phase but on a very different time scale.

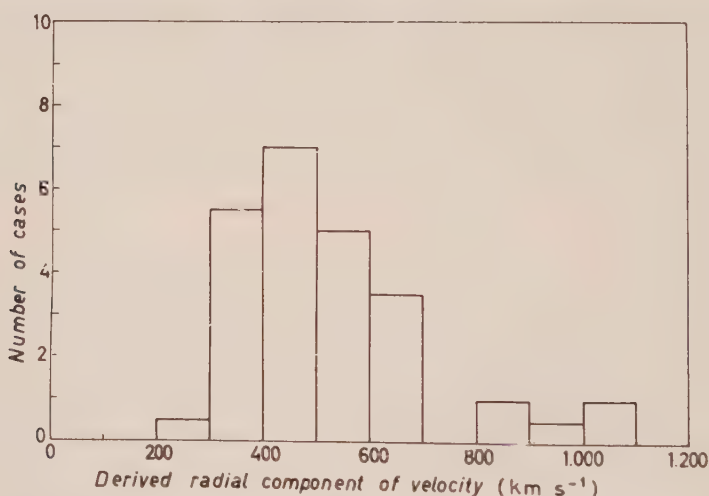


Fig. 8. Distribution of the radial components of velocities of type II bursts derived from spectral data and the assumption of a standard model atmosphere (ROBERTS). Subsequent interferometer observations indicate that these velocities should be increased by a factor of 2 or 3.

Type II bursts are reminiscent of type III bursts in which the time scale has been elongated by a factor of some 200; and the same relation roughly holds between type IV and type V bursts. It is natural therefore to interpret types II and III by the same physical mechanism, and likewise types IV and V.

Application of the plasma hypothesis to type II bursts leads to derived velocities of the order of 500 km/s when a standard model corona is assumed (see histogram due to ROBERTS [7] in Fig. 8) but as with type III bursts, interferometric observations [13] indicate that the disturbances travel through regions of much higher density and that the velocities in Fig. 8 should be increased by a factor of between 2 and 3. Hence we appear to be dealing with a disturbance which travels out from the flare with a velocity in the range $(1000 \div 1500)$ km/s. Such velocities are about 10 times the velocity of sound in the corona, suggesting that the disturbance may be some kind of shock wave. Their interpretation in terms of magneto-hydrodynamical shock waves has been discussed by WESTFOLD [19].

5.1. *Special features of type II bursts.* — During the slow development of a type II burst, there unfolds a mass of complex details, often repeated with remarkable fidelity at the second-harmonic frequency. No two events are quite alike, but certain features recur with sufficient regularity to demand attention. Of these, the most prominent is the splitting of each main band into two sub-bands (see Section 2.2). The only reasonable explanation which has been suggested to explain this effect is a kind of magnetic splitting analogous to the Zeeman effect [1, 7]. The explanation is not confirmed by polarization observations which indicate only random polarization; nor is it exactly consistent with the existing theory which predicts double splitting in the fundamental and *treble* (instead of double) splitting in the harmonic. However, the amount of splitting is quantitatively consistent with coronal magnetic fields due to sunspots (ROBERTS [7]).

A second feature of special interest is the occasional appearance of what appear to be type III bursts actually emanating from the main type II bands and proceeding out to lower frequencies [7]. Sometimes these are accompanied by others with reverse frequency drift proceeding to higher frequencies, and so the resulting dynamic spectrum has a «hering-bone» appearance. The phenomenon appears to indicate the ejection of relativistic particles from the type II disturbance both away from and towards the Sun.

6. — Interpretation of type IV bursts.

The significance of type IV bursts was first recognized from interferometric observations, spectral data being used as subsidiary information. From his observations with the 169 MHz grating interferometer at Nançay, BOISCHOT [3] concluded that the emissions first appeared high in the corona and moved, with velocities similar to those of the type II disturbances that preceded them, to even greater heights (up to 3 or 4 solar radii), where they remained for

several hours before falling back into the Sun. This behaviour, combined with the great breadth of the spectrum was inconsistent with an origin in plasma oscillations and prompted the suggestion of a synchrotron theory.

Boischot's synchrotron theory (cf. Section 4) leads to the requirement of maintaining electrons with energies of a few MeV in the source region for a period of hours. If the electrons are trapped in a suitable magnetic field configuration, there seem to be no theoretical objections to this requirement because the relativistic electrons should not lose appreciable energy either by collisions or radiation in this period.

The physical difference between type II and type IV events, as predicted by the theory, that the first is due to plasma radiation and the second to synchrotron, has recently been directly demonstrated [13] by observations with the Dapto swept-frequency interferometer. It was found during a limb flare that while the type II radiation originated at different levels according to the frequency, the type IV radiation originated, at any one time, at the same general level irrespective of frequency. The latter condition was maintained while the source moved out from the Sun, eventually fading at a height of some 4 solar radii.

6'1. *On the common link between type II and type IV disturbances.* — BOISCHOT [3] pointed out that the time delay (~ 20 minutes) between the start of the flare and the start of the type IV burst was about the same as that required for a disturbance to travel from near the photosphere to the height of the type IV source at velocities derived for type II bursts. He therefore suggested that the type II burst signified the outward transportation of the cloud of relativistic electrons needed for the type IV emission. This idea has recently been extended by McLEAN [16], who has proposed the model disturbance illustrated in Fig. 9 at 4 stages of its development. The model assumes an initial explosion which ejects high-energy particles. These particles are constrained in the strong local magnetic field (envisaged as that due to a bi-polar sunspot group), and the disturbance moves outwards behind the front of a magneto-hydrodynamic shock-wave, carrying with it the magnetic field. The shock front is identified with the type II source, and the energetic particles in its wake as the type IV source.

6'2. *On the common link between first and second phases of the complete radio flare-event.* — In the foregoing interpretation we have linked first the type III and type V bursts by a common disturbance travelling at a velocity of about $\frac{1}{2}c$ and containing MeV electrons, and secondly the type II and the type IV bursts by a common disturbance, also containing MeV electrons, but travelling at a velocity of about 1000 km/s. The ultimate question as to how these two disturbance are linked was first discussed by WILD, ROBERTS and MURRAY [9, 7],

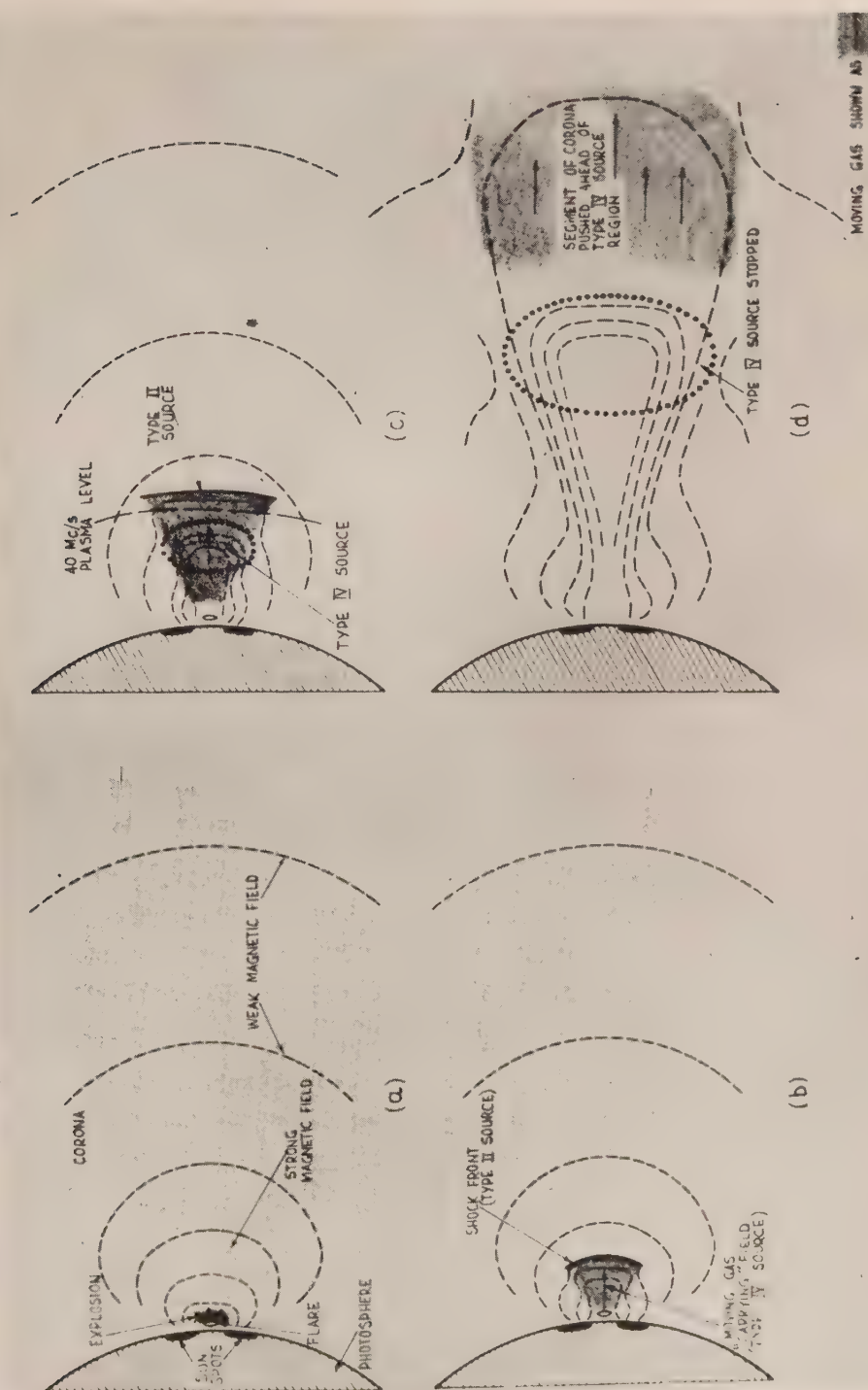


Fig. 9. Four phases in the evolution of the second phase of radio outbursts according to a model proposed by McLEAN.

who pointed out that the time and velocity relationship between first and second phases was consistent with the idea that both originated simultaneously in the same «explosion» near the photosphere. Further enlightenment came from Giovanelli's [17] result that the time of the «explosion» (as indicated by the sudden onset of the type III bursts) coincided with the initial rapid expansion of the H_α -flare. On current interpretations, therefore, it appears that we need an explosion near the photosphere which 1) causes a sudden increase in the emission of H_α -light, (and presumably quanta of higher energy), 2) ejects a stream of relativistic electrons which escapes immediately into the outer layers of the corona and beyond and 3) sets up a shock-wave which carries with it further relativistic electrons. The physical nature of this explosion is among the most fascinating of the unsolved problems in solar physics.

7. – Geophysical effects.

Since the radio emission from flares is related to the ejection of solar particles, we might expect that a search for relations with geophysical phenomena would prove profitable. At the present time, two aspects seem highly promising, *viz.* cosmic-ray increases and geomagnetic storms.

7.1. *Cosmic-ray increases.* – The occasional large increases in the flux of cosmic rays at the earth following flares start some $(10 \div 30)$ minutes after the start of the flare, despite the relativistic velocities of the particles. Hence either the velocity of the cloud of particles must be slower than the velocity of the individual particles, or their emission from the Sun must be delayed.

The first possibility was envisaged by WILD, ROBERTS and MURRAY [9] in a suggestion that particles in the type III disturbance ($v < c$) may correspond to cosmic rays. However, type III bursts are very common and cosmic-ray increases exceedingly rare, and no evidence to support the relation has yet come to light. Observations from rockets and satellites could clarify this question.

The second possibility was envisaged by BOISCHOT and DENISSE [3], who pointed out that the time delay associated with cosmic ray increases was about the same as that associated with type IV bursts, and suggested that the type IV source was responsible for ejecting the cosmic rays. This suggestion is particularly attractive, since both kinds of event are rare and associated only with outstanding flares. It receives strong support from the fact that each of the 3 or 4 large cosmic-ray increases which have occurred since the advent for radio observations have been accompanied by what appear to be type IV bursts.

7.2. *Geomagnetic storms.* — The recognition of sudden commencements of terrestrial magnetic storms ($1 \div 3$) days after large flares had long ago led to a causal hypothesis in terms of a corpuscular stream from the flare with velocities of about 1000 km/s. This immediately suggests a relationship with the second phase of the radio outburst. Indeed the relationship was first suggested as early as 1947, before the start of spectrographic observations, when PAYNE-SCOTT, YABSLEY and BOLTON [20] discussed a radio outburst at 3 single frequencies in which higher frequencies arrived before lower frequencies. The subsequent recognition of the type II burst substantiated this suggestion [6]. Velocities derived at that time (~ 500 km/s) seemed rather low, but this difficulty is probably removed by the interferometer observations previously described.

The temporal correlation between the radio bursts and geomagnetic storms gives the most direct test of the relationship. Such a correlation was published by DODSON [21] in 1958 using single-frequency radio data. She found that the significant radio event appeared to be the occurrence of a major burst *preceding* the maximum of the flare, *i.e.* presumably the first-phase. This result gave no support to the prediction that the second phase was responsible. In a subsequent investigation, using spectral data, ROBERTS [7] found that the correlation between type II bursts and geomagnetic storms was significant beyond doubt (though by no means 1:1), while no significant correlation with type III bursts was present. He gave evidence for suggesting that the apparent disagreement with Dodson's results was due to a large number of compound (first and second phase) events being included in Dodson's analysis.

While Roberts' results on type II bursts confirmed the predicted relationship with the second-phase of the radio outburst, there remained the question of the role of the type IV burst. An investigation by SINNO and HAKURA [22] indicated that the type IV burst rather than the type II was the significant event, and that the probability of a geomagnetic storm occurring after a type IV burst was high. This result has recently been substantiated by an analysis of McLEAN [16]. While the data available to him were insufficient to state a firm conclusion, his results indicated a remarkably close connection between the type IV burst and the geomagnetic storm. The result may find an explanation in the general idea that the presence of a type IV burst is an indication of the amount of matter transported from the flare by the second-phase disturbance.

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Interpretation of Solar Radio-Observations.

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Sterrenwacht - Utrecht

I.

The Spectrum of the Quiet Minimum Sun's Disk Centre.

The basic observational data referring to the radiation of the quiet sun are known. We summarize them briefly:

a) The intensity of the quiet sun's disk centre, if expressed in temperatures ($T_b(0)$ = brightness temperature of the disk centre) increases from about $6\,000^\circ$ near $\lambda = 1$ cm to 10^6 °K at meter waves (Fig. 1).

b) $T_b(0)$ varies during the undecennial cycle. Fig. 9 of Hachenberg's lectures gives $T_b(0)$ at sunspot maximum (1947) and minimum (1954).

c) The intensity varies across the disk (see Chapter II).

d) No polarization of the quiet sun's radiation has been detected.

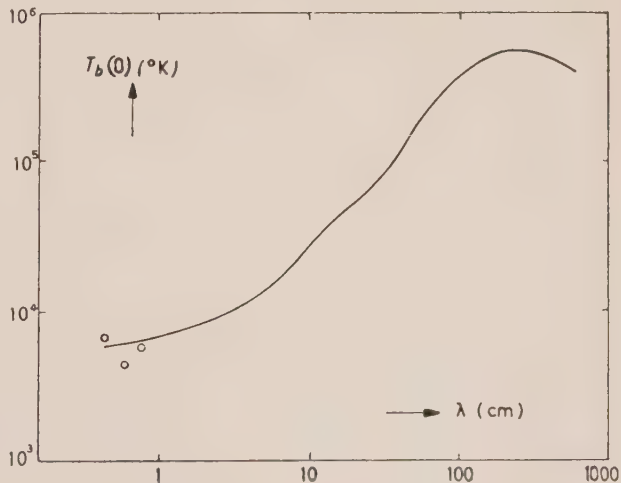


Fig. 1. — Brightness temperature for the disk centre [$T_b(0)$] for the quiet minimum sun (minimum of 1954). Open circles indicate some observations made in the mm region; see Sect. 3.

c) The outer solar corona acts as a scattering medium for point source radiation lying behind (occultations of *Tau A*).

These data should be used to derive an appropriate model of the outer solar atmosphere. This model should at the same time agree with the increasingly rich information derived from optical data and with the aid of rockets. It should take into account: a) the variation of T and N_e with height; b) the circular asymmetry of the chromosphere and corona; c) the inhomogeneity of the chromosphere shown by optical observations; d) the inhomogeneity of the corona, shown mainly by radio-observations. Finally it should be inquired whether such a model, once being derived, can be understood physically.

In fact, the structure of the quiet corona varies continuously, and in this respect the notion « minimum corona » seems to be better defined than that of « the » maximum corona. The ideal minimum corona seems to be best approximated by that of 1954. In this Chapter we only deal with the curve $T_b(0)-(\lambda)$ giving the brightness temperature T_b for the disk centre, of the quiet minimum sun (1954) (see Fig. 1).

1. — The continuous absorption coefficient.

The brightness temperature at the disk centre is

$$(1.1) \quad T_b = \int_0^{\infty} T_e(\tau_\lambda) \exp[-\tau_\lambda] d\tau_\lambda.$$

Here T_e is the kinetic temperature of the electron gas, virtually equal to that of the ion-gas; further τ_λ is the optical depth for a wavelength λ , related to the absorption coefficient κ_λ by

$$\tau_\lambda = - \int_{\infty}^h \kappa_\lambda dh.$$

We shall further omit the suffix λ . The absorption coefficient κ is due to free-free transitions of electrons in the fields of ions. The problem to compute κ has been discussed by various authors. An expression for the absorption coefficient is usually found by first deriving one for the emission. The total emission Q of one electron in one passage along a ion is related to its acceleration $\ddot{r} = Ze^2/mr^2$ by

$$Q = (2e^2/3c^3) \int_{-\infty}^{\infty} (\ddot{r})^2 dt.$$

The usual way of computing the total emission $4\pi\epsilon$ of an electron gas goes in three steps, first by finding the spectral distribution of the radiation emitted by one electron, applying Fourier analysis to $\ddot{r}$; next by performing the integration over all values of the collision parameter b , being the smallest distance between the two particles if they would have moved along straight lines and finally by integrating over all velocities. In a classical treatment b should range between a smallest value 0 for returning particles, and an upper value. Divergencies would occur if b would be allowed to go to infinity. Differences between results of various authors arise from the different choices of the integration limits. According to SPITZER the upper limit should be equal to the Debye length h (being a measure for the distance in a gas along which $\tilde{n}_e \neq n_e \tilde{Z}$). A recent very complete discussion, on the classical basis, by OSTER [1] yields results very slightly different from those found by ELWERT [2] quantum-mechanically.

After having found $4\pi\epsilon$ we put (Kirchhoff's law) $4\pi\epsilon = \kappa B(T)$, where B is the blackbody radiation of the gas, $B(T) = 2kf^2T/c^2$; f is the frequency. Kirchhoff's law is only valid in thermodynamic equilibrium, but here recourse has been made to the equilibrium case to find a function $\langle\kappa_\lambda\rangle$ that is also valid in non-thermodynamical equilibrium. For practical purposes (application to the sun) one often writes

$$\kappa = \zeta N_e^2 / n f^2 T_e^{\frac{3}{2}},$$

$$\zeta = 1.32 \cdot 10^{-2} \ln(367 T N_e^{-\frac{1}{2}}),$$

$$n = \text{the refractive index} = (1 - f^2/f_0^2)^{\frac{1}{2}},$$

$$f_0 \text{ is the plasma frequency} = (e^2 N_e / \pi m)^{\frac{1}{2}} = 8.98 \cdot 10^{-3} \sqrt{N_e} \text{ (MHz)},$$

ζ is a slowly varying function of T_e and N_e . For practical use values for ζ are found by inserting for each wavelength the solar values for T_e and N_e at those heights where the radiation of that wavelength is mainly emitted:

$$\lambda \quad = \quad 1 \quad \quad 3 \quad \quad 10 \quad \quad 30 \quad \quad 100 \quad \quad 300 \quad \quad 600 \text{ cm.}$$

$$\zeta_{\text{Elwert}} = 0.085 \quad 0.097 \quad 0.124 \quad 0.15 \quad 0.17 \quad 0.18 \quad 0.18$$

Oster's expression gives slightly different results. *E.g.* for assumed values:

$$\log f = 9, \log N_e = 8.5 \text{ and } \log T_e = 5, \text{ we obtain } \zeta_{\text{Elwert}} / \zeta_{\text{Oster}} = 0.75.$$

For $\log f = 11, \log N_e = 10, \log T_e = 3.7$, we get for this ratio: 1.15.

The differences are at the present time of no importance but they will be in a few years when our knowledge of the corona has increased further.

2. - Preliminary interpretation of the spectrum of the quiet minimum disk's centre

We approximate (1) as follows:

(1.2)
$$T_b = \int_0^\infty T_e \exp [-\tau] d\tau \approx T_e (\tau=1).$$

Now

(1.3)
$$\tau = \zeta f^{-2} \int_h^\infty N_e^2 T_e^{-\frac{3}{2}} dh ,$$

hence $\tau=1$ may be reduced to

(1.4)
$$\zeta f^{-2} N_e^2(h^*) T_e^{-\frac{3}{2}}(h^*) H_\varkappa = 1 ,$$

where $H_\varkappa$ is the scale height of $\varkappa$, *i.e.* the range of height on which $\varkappa$ has changed by a factor e ; h^* is the geometrical height for which $\tau=1$.

A simple way to compute the $T(h)$ relation from the given continuous spectrum is the following: Assume an N_e distribution, *e.g.* the one given by optical data. Compute as a first approximation $H_\varkappa^{(1)} = (d \ln N_e^2/dh)^{-1}$, and find $T_e^{(1)}(h^*)$ by computing for any given value of $T_b(\lambda)$ the height $h^{(1)}(\lambda)$ for which

(1.5)
$$\zeta f^{-2} = T_b^{\frac{3}{2}} N_e^{-2}(H)^{-1} .$$

The first part of this expression depends only on λ ; the second on h . The solution of (1.5) fixes a relation between λ and h , hence between h and $T_b = T_e$, hence yields $T_e^{(1)}(h)$.

Second approximation: With the relation between T_e and h thus found we look for the height $h^{(2)}(\lambda)$ for which

$$\zeta_\lambda f^{-2} T_b^{-\frac{3}{2}} N_e^2 (d \ln (N_e^2 T_{e1}^{\frac{3}{2}})/dh)^{-1} = 1 .$$

This gives a second approximation to the $T_e(h)$ curve, etc.

An example of such a computation is shown in the following Table.

$h/1\,000\text{ km} = \log N_e\text{ (cm}^{-3}\text{)}$	2.0	3.0	4.0	6.0	8.0	10.0	20.0	40	80	150	300
	10.65	10.33	10.02	9.45	8.95	8.61	8.26	8.13	7.89	7.56	7.05
$\log \lambda\text{ (cm)}$	−0.4	0.0	0.4	0.8	1.2	1.6	2.0	2.4	—	—	—
$\log T\text{ (}^\circ\text{K)}$	3.76	3.86	3.98	4.23	4.64	5.06	5.59	5.5	—	—	—
$\log h^{(1)}\text{ (km)}$	3.51	3.75	3.83	3.89	(4.3)	4.77	4.82	5.36	—	—	—
$\log h^{(4)}$	3.68	3.76	3.83	3.90	4.00	4.09	4.29	—	—	—	—

The first four points of the first approximation agree reasonably well with heights derived by a more sophisticated method. The last points disagree considerably, due to the neglect of the temperature term in the scale height. A second approximation taking the temperature term into account gives a better agreement. The Table also contains $\log h^{(4)}$ obtained in fourth approximation.

A more elegant but not more accurate method is Piddington's [3].

Expand

$$(1.6) \quad T_b = A + Bf^{-1} + Cf^{-2},$$

where T_b is given by (1.1) with $\tau_\lambda = \alpha f^{-2}$ and

$$(1.7) \quad \alpha = \zeta \int_h^\infty N_e^2 T_e^{-\frac{3}{2}} dh.$$

Hence, from (1.6) and (1.7):

$$(1.8) \quad Af^2 + Bf + C = \int_0^\infty T_e \exp[-\alpha f^{-2}] d\alpha.$$

The solution of this integral equation (Laplace transformation) is

$$(1.9) \quad T_e(\alpha) = A + B(\pi\alpha)^{-\frac{1}{2}} + C \cdot \delta(\alpha),$$

where the δ function in the last term represents a discontinuity for $\alpha = 0$ (high temperature in the corona); the other terms represent the transition region chromosphere-corona. Adopting some $N_e(h)$ distribution, $T_e(h)$ can be found.

The ambiguity of all these results ($N_e(h)$ should be known to find $T_e(h)$) can only be escaped by using more detailed data. The centre-limb variation of the solar radioradiation will be discussed in Chapter II.

3. - Inversion at very short wavelengths?

An interesting region occurs at very short wavelengths, where the influence of the inhomogeneities of the chromosphere may become visible. The following brightness temperatures have been measured around the minimum of 1954 (see Fig. 1):

$\lambda = 4.3$ mm	$T_b = 7\,000^\circ$	[4]
6.0	$4\,500^\circ \pm 400^\circ$	[5]
7.5	$6\,000^\circ \pm 500^\circ$	[6]
8.6	$8\,500^\circ$	[4].

Apparently T changes only slightly in the chromospheric regions where this radiation is emitted. Assume for a moment $T = \text{constant}$, then, $H_x = \frac{1}{2} H(N_e) \approx 500$ to 1000 km. With (1.4) and $H_x = 700$ km we find at 7.5 mm: $\log N_e = 10.0$, yielding the average emission height $h^* = 4300$ km. For 6.0 and 4.3 mm we thus find $h^* = 4000$ km and 3500 km. That $T_b(4.3 \text{ mm}) > T_e(6.0 \text{ mm})$ is perhaps due to the influence of the chromospheric temperature inhomogeneities making the average temperature higher if the number of hot elements increases. Assuming for the cool and the hot elements at 3500 and 4000 km temperature of 5000° and 15000° respectively, one finds that at 3000 km the volume occupied by the hot elements should be about 20% to explain $T_b(4.3 \text{ mm}) = 7000^\circ$; it is considerably smaller and cannot be determined thus at the greater heights.

The measurements are very difficult at these short waves so that the above conclusion is far from certain. The present discussion is only intended to draw the attention to the problem posed by this interesting region of the spectrum. An extension of the measurements to 1 mm and shorter would be highly desirable.

4. - The decrease of brightness temperature at long wavelengths.

The observations show that the apparent disk temperature T_o decreases for $\lambda > 3$ m. The value of T_b decreases also since the area under the curves $T_b(r)$ increases with increasing wavelength. This result should not necessarily indicate a decrease of T_e with increasing height in the corona; there is in any case no optical evidence that T_e decreases for $q (= r/R, \text{ taken from the sun's centre}) < 3$. Theoretically we would expect a negligibly small decrease of temperature over the first 10^6 km, because of the great conductivity of the coronal gas.

Another explanation for the decrease of T_e with increasing wavelength was suggested by WILD at the colloquium: For long wavelength the turning points of the rays lie so high in the corona that the total optical depth measured along a ray path becomes of the order unity or even smaller. So, at long wavelengths the sun might be a «gray» body.

The effect is mainly important for non-central rays but as a whole it is of small importance. *E.g.* the old computations of BURKHARDT and SCHLÜTER [7] yield the following values for the ratio between the brightness temperature of the sun and that of a blackbody with the same temperature:

at 5 meter:	1.0
10	0.9
15	0.75.

Other computations give similar results.

So it seems much more probable that the negative value of $dT_b/d\lambda$ is to be ascribed to irregular refraction (often called «scattering») in the outer corona. Such a kind of refraction would not result in a decrease of T_b if the sun had no limb darkening and if it were infinitely large; the decrease of T_b is due to the fact that the scattering angle of radiation is greater than* the apparent diameter of the sun. Cf. Fig. 2, where the dotted line gives the $T_b(r)$ curve obtained with scattering. That the areas of both curves are not equal is caused by the fact that on the average the scattered rays become longer and are thus more absorbed.

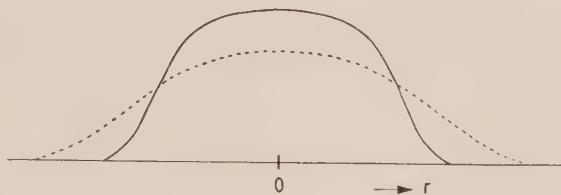


Fig. 2.

5. — Summary.

This discussion of the solar $T_b(0)-\lambda$ curve shows:

- 1) the well-known increase of T_b from the chromosphere to the corona;
- 2) the importance of observations in the mm range;
- 3) the influence of coronal scattering, reducing the brightness temperature for long wavelengths.

Especially this latter point will be discussed in more detail in the next Chapter.

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II.

Centre-Limb Variation of the Solar Radiointensity; Scattering.

Fig. 3 (DE JAGER [1]) shows the variation of the solar brightness temperature across the disk. For more detailed pictures see WILD: *Solar Radio Interferometry*, Figs. 6a and 6b (this volume p. 292, 293); and HACHENBERG, Fig. 10 (this volume, p. 235). All observations refer to the quiet minimum sun and have been obtained around the minimum of 1954. The essential

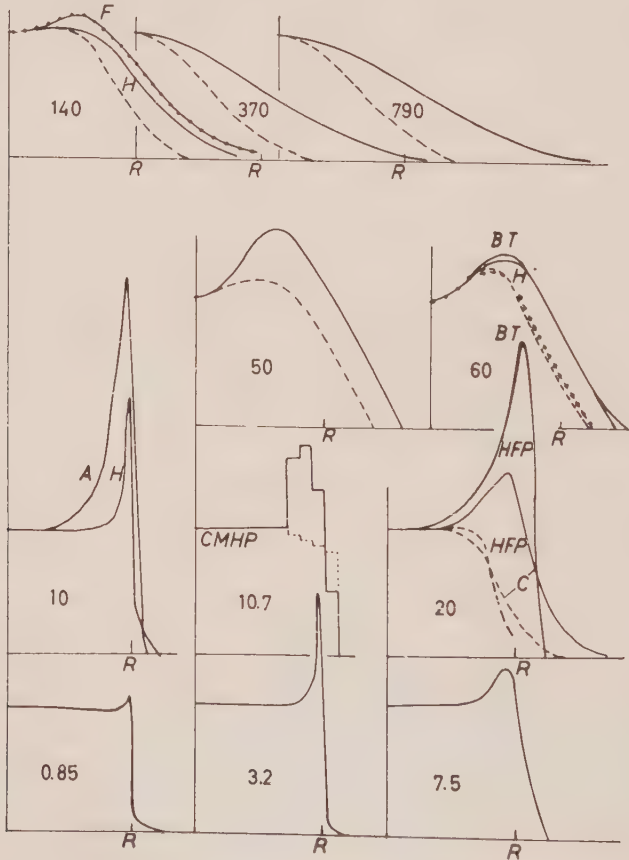


Fig. 3. — Brightness distribution of the sun. The wavelengths (cm) are indicated in each graph. When two lines are given, the solid one gives the equatorial brightness distribution, the dashed one gives the polar distribution (see DE JAGER [1], Fig. 97).

features are:

- 1) The bright equatorial limb segments, most pronounced around $\lambda = 20$ cm.
- 2) The spherical asymmetry. A polar limb brightening does not occur.
- 3) The displacement of the brightness maximum towards the centre for increasing λ and its disappearance for meter waves.
- 4) The increase of the sun's apparent diameter with increasing λ .

1. - The equatorial brightness distribution.

It is our hope that the complete information, nowadays available about the equatorial brightness distribution, if transformed into absolute units, could yield a better $T_e(h)$ curve, and perhaps at the same time independently give the $N_e(h)$ curve, at least for $h > 20\,000$ km where N_e is badly known. Here in any case the height h is known but for an unknown constant amount, being of the order of the position measuring uncertainty $1'.5$ to $3'$, i.e. $40\,000$ km to $80\,000$ km. The precise value of the constant can always be fixed afterwards by means of optical data.

The $T_e(h)$ and $N_e(h)$ functions are found by trial and error; no direct analytical method has as yet been proposed.

a) Start with given $T_e^{(1)}(h)$ and $N_e^{(1)}(h)$ functions and compute the corresponding first approximation $T_e^{(1)}$ for different λ and for different places on the disk, given by the parameter a (Fig. 4). Thereby the curvature of the ray path due to refraction has to be taken into account for $\lambda > 0.5$ m; the integration (1.1) is made along a ray trajectory defined by the Snellius equation: $nr \sin i = a$ (cfr. COUTREZ: *Le soleil calme*, this volume, p. 167).

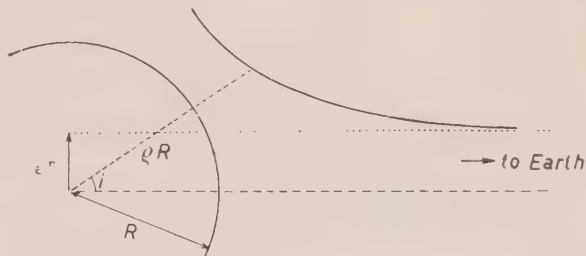


Fig. 4.

For a spherically symmetric corona

$$(2.1) \quad i = a \int_{\varrho}^{\infty} \frac{d\varrho}{\varrho \sqrt{n^2 \varrho^2 - a^2}}.$$

It will then be found that $T_b^{(1)}(a, \lambda)_{\text{comp}} \neq T_b(a, \lambda)_{\text{obs}}$. Next we wish to transform $\Delta T_b(a, \lambda) (= T_b(a, \lambda)_{\text{obs}} - T_b(a, \lambda)_{\text{comp}})$, or still better: $\Delta \log T_b$, into corresponding quantities $\Delta \log T_e(h)$ and $\Delta \log N_e(h)$. So we wish to write

$$(2.2) \quad \Delta \log T_b(a, \lambda) = A \Delta \log T_e(h^*) + B \Delta \log N_e(h^*),$$

where h^* is the average height of emission.

Of course a deviation in T_b cannot be attributed to a single height h^* : T_b is obtained after an integration over the depth, from zero to infinity. But since the region of depth that contributes effectively is only narrow, the above procedure is possible if h^* varies only little with height.

A fairly rapid semi-empirical way to determine A and B is the following. After having performed the integration (1.1) along the ray paths as indicated here, the same integration is made twice again but now for τ -values which at all heights are respectively two times greater and two times smaller than the correct values; $T_e(h)$ remains the same. This yields two new T_b values: T_b'' and T_b' . So we obtain

$$\frac{\Delta \log T_b}{\Delta \log \kappa} = \frac{\log (T_b''/T_b')}{0.60}.$$

further

$$(2.3) \quad \Delta \log T_b = \left(\frac{\partial \log T_b}{\partial \log T_e} \right)_{\kappa} \Delta \log T_e - \frac{\partial \log T_b}{\partial \log \kappa} \Delta \log \kappa = \Delta \log T_e - \frac{\partial \log T_b}{\partial \log \kappa} \cdot \frac{\partial \log \kappa}{\partial \log T_e} \Delta \log T_e + \frac{\partial \log T_b}{\partial \log \kappa} \cdot \frac{\partial \log \kappa}{\partial \log N_e} \Delta \log N_e = \left(1 - \frac{3}{2} \frac{\Delta \log T_b}{\Delta \log \kappa} \right) \Delta \log T_e + 2 \frac{\Delta \log T_b}{\Delta \log \kappa} \Delta \log N_e.$$

So A and B are defined.

Further, for each λ and a -value the height h^* is determined for which $\tau_{\lambda a} = 1$.

Obviously, different λ and a 's can yield similar h^* values. By grouping together all computations referring to the same h^* , we get for each of these h^* values a set of equations from which $\Delta \log T_e(h^*)$ and $\Delta \log N_e(h)$ can be derived. Such an investigation, still underway yielded the $T_e(h)$ and $N_e(h)$ curves shown together with the « best » solar $N_e(h)$ and $T_e(h)$ curves in Figs. 5 and 6.

The derived densities (Fig. 5) well agree with other results, the temperatures less so (Fig. 6). For heights smaller than about 15 000 km there seems to be a shift along the $\log h$ -axis between the temperatures deduced from radio and

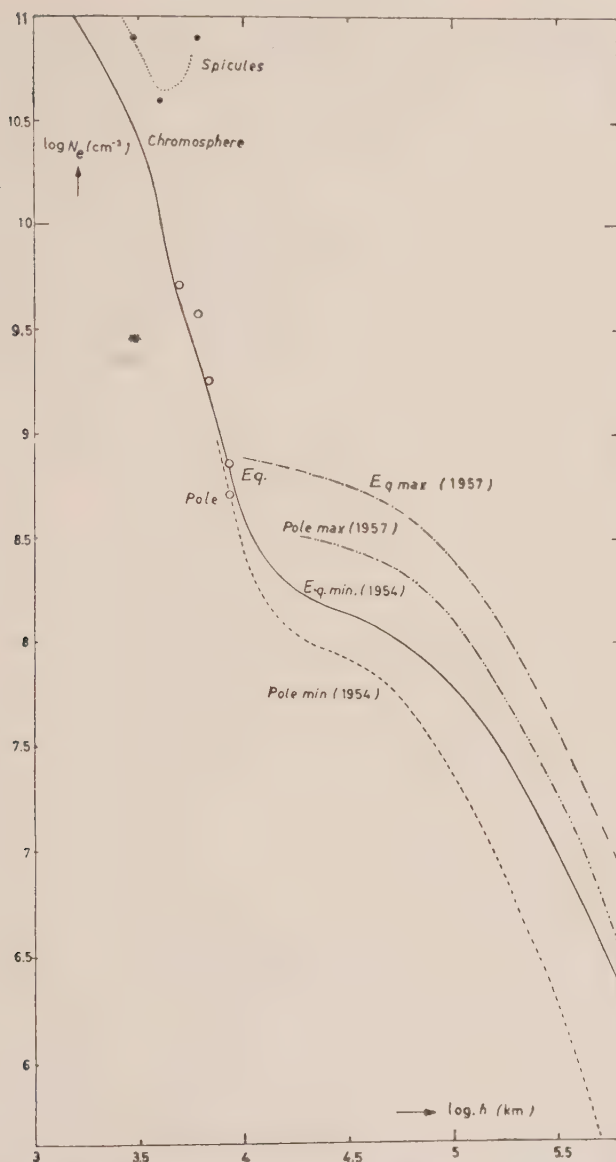


Fig. 5. Electron densities in the chromosphere and the corona; after a compilation of recent observations made by the author [DE JAGER, [1] Tables 7 and 17]. Four curves are given for the *corona*: for the equator and pole of the minimum corona (1954, mainly from eclipse observations), and the maximum corona (1957, mainly from coronameter observations, and for great distances from the earlier compilation by Van de Hulst). For the *chromosphere* distinction has been made between the main chromosphere (solid line, smoothly connected to the minimum equatorial corona), and the spicules, resp. the hot elements of the low chromosphere. In that latter region the densities are badly known (filled circles and dotted line), but they seem higher than those of the main chromosphere. The *open circles* give the electron densities as determined from the radio-observations as described in Sect. 1 of this chapter.

optical data. For larger heights the equatorial and polar temperatures seem definitely too small. This again shows the influence of « scattering ».

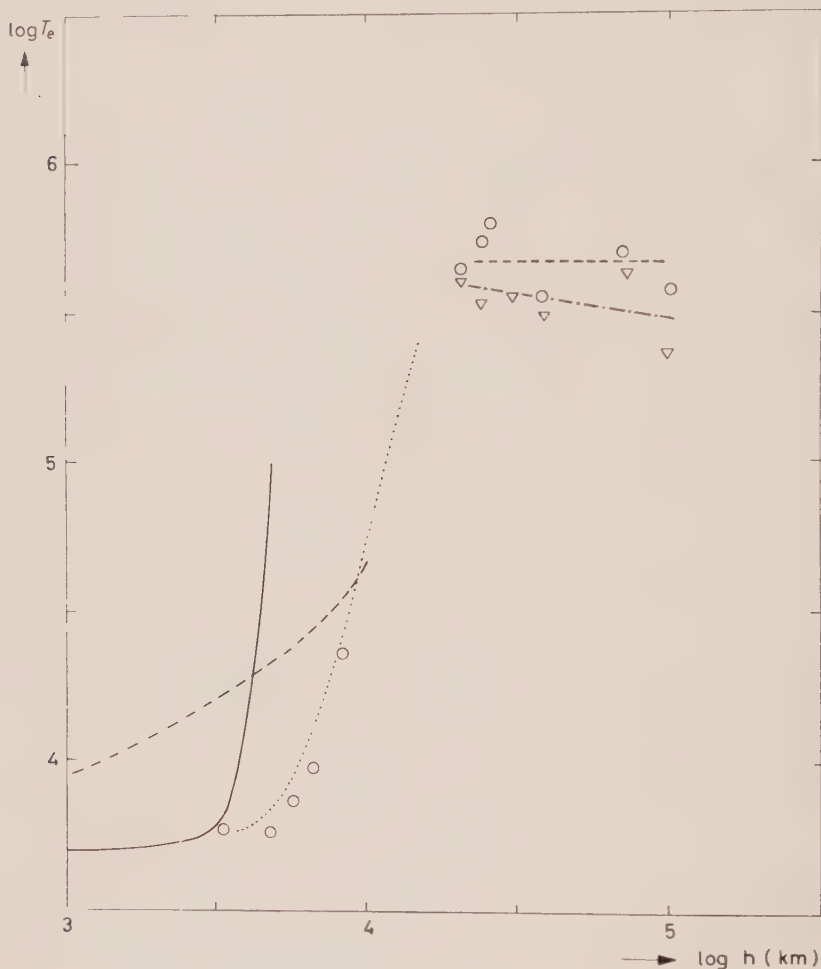


Fig. 6. Temperatures in the chromosphere and corona. *Solid line*: temperature in the chromosphere derived from optical data. *Dashed line*: temperatures in the hot elements of the chromosphere and the spicules. *Open circles and dotted lines*: equatorial temperatures deduced from the radiobrightness distribution of the sun. *Triangles*: polar temperatures.

Another way to compare the observations with the computations is to plot, following ALLEN, the computed and the observed values of $T_b(l)/T_b(0)$, where $T_b(l)$ is the brightness temperature of the peak of the equatorial segment, or if this does not exist, the T_b of the limb ($l = R$) (Fig. 7).

Fig. 7. — Comparison of the observed and the computed values of $T_b(l)/T_b(0)$ where $T_b(l)$ is the brightness temperature of the peak of the equatorial segment, or if this does not exist, the brightness temperature of the limb ($r=R$). The observations (circles) are deduced from our Fig. 3; the computational results (solid lines) are derived from unpublished computations made at Utrecht on the basis of the N_e -distribution of Fig. 5 (minimum equator) and of the temperatures given in Fig. 26 of the author's paper in the *Handb. d. Phys.* [DE JAGER [1]].

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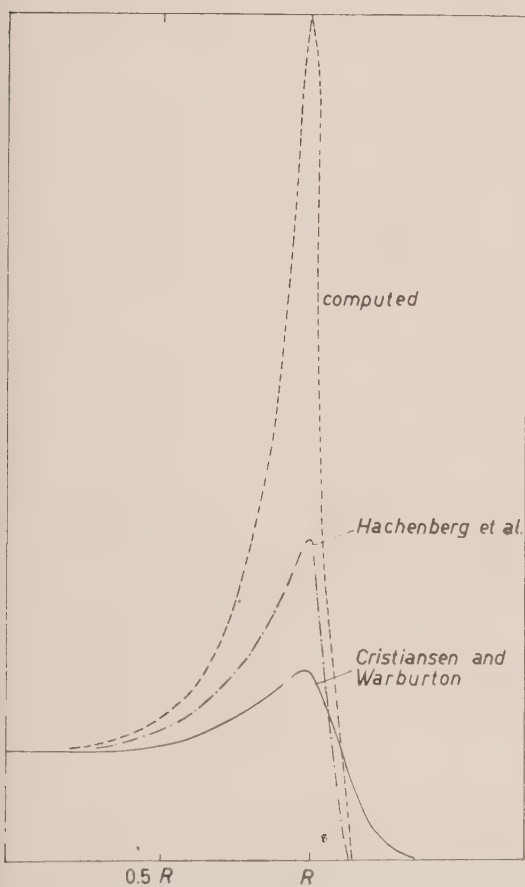
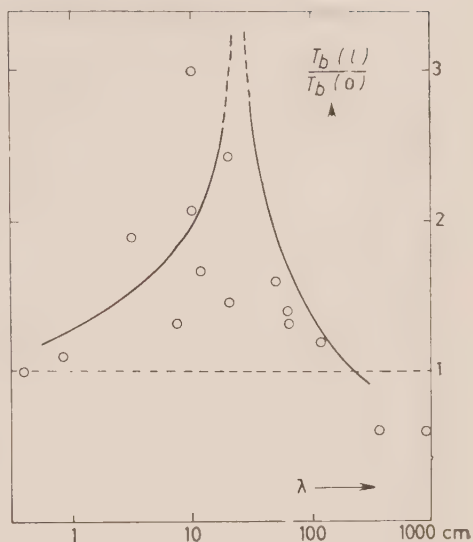


Fig. 8. — Comparison of the observed and the computed brightness distribution at 21 cm. Observations and computations have been normalized to the same intensity at the disk centre. In the computations the influence of scattering has *not* been

taken into account. References of observations: O. HACHENBERG, F. FÜRSTENBERG and H. PRINZLER: *Zeits. f. Astrophys.*, **39**, 232 (1956); W. N. CHRISTIANSEN and J. A. WARBURTON: *Austral. Journ. Phys.*, **8**, 484 (1955).

Below 10 cm and above 80 cm the computations and observations agree but near 20 to 40 cm there is a disagreement, that might partly be due to lack of resolving power of the observations, partly perhaps to the influence of scattering, which tends to widen the very narrow peaks. See the example (Fig. 8) for 21 cm. It should be added that the *computations* are also somewhat uncertain at this wavelength since a slight uncertainty in the computations for the limb rays may cause that the ray just hits or misses the region where the temperature steeply ascends to coronal values. Nevertheless, also here the influence of scattering seems clear. It will be made acceptable in Chapter III that also the differences between the brightness distributions at the pole and equator may be explained by the mechanism of scattering.

2. - Irregular refraction in the solar atmosphere.

There are four kinds of objects useful to study irregular refraction, usually called « scattering », in the corona:

- a) The limb peaks at about 30 cm refer to scattering at $h^* \approx 10\,000$ km;
 - b) the wings at meter waves refer to $h^* \approx 300\,000$ km;
 - c) the measurements of occultation of *Taurus A* refer to $\varrho (= r/R_\odot) > 4.7$, or $h^* > 2\,600\,000$ km;
 - d) the angular diameters of sources of stormpips are large, their true diameter may be small; $h^* \approx 300\,000$ km (FOKKER, this volume, p. 374).
- b) and c) have been investigated, a) and d) hardly.

The points b) and c) will be discussed here; d) will be treated cursorily in Chapter VII.

For the mathematical description of the scattering process distinction has to be made between two cases: the scattering of radiation by a plane parallel layer (case of *Tau A* occultations), and the scattering of radiation in a self emitting atmosphere (points a), b) and d)).

3. - Scattering by a plane-parallel layer.

Different authors have discussed the problem of irregular refraction; we shall give a short summary, following SCHEFFLER [2]. We consider a plane wave parallel to the x - y plane, passing an inhomogeneous medium between the planes $z = 0$ and $z = Z$, where Z is large as compared to the scale of the inhomogeneities. After having passed this medium at $z = Z$ the wavefront is

no longer plane but may be thought of as composed of an infinite number of plane waves, inclined with small angles Θ and Φ to the x - z planes. The different waves will also arrive with a different phase in the plane $z = Z$. Let each of these waves be given by

$$A_z(\Theta, \Phi) \exp [i\omega(x\Theta + y\Phi)],$$

then A_z will be related to the distribution of electrical field-strengths $E(x, y, Z)$ by the Fourier transformations

$$E(x, y, Z) = \int_{-\infty}^{\infty} A_z(\Theta, \Phi) \exp [i\omega(x\Theta + y\Phi)] d\Theta d\Phi$$

and

$$A_z(\Theta, \Phi) = \frac{1}{\lambda^2} \int_{-\infty}^{\infty} E(x, y, Z) \exp [-i\omega(x\Theta + y\Phi)] dx dy.$$

Next we proceed as follows:

Assume that the field-strength distribution in $z = Z$, the distribution of the phases in $z = Z$ and the distribution of the scattering index n in the passed volume can all be given by correlation functions, these being functions of type:

$$\sigma(\zeta) = \frac{f(\mathbf{r}) f(\mathbf{r} + \zeta)}{f(\mathbf{r})^2}.$$

For the correlation function of the refractive index we assume moreover the special form

$$\sigma(\zeta) = \exp [-\zeta^2/l^2],$$

where l is the characteristic scale of the inhomogeneities. The relations between these three correlation functions have been derived by various authors and so the whole further problem is one of algebra; it is further simplified by assuming isotropic scattering. In that line SCHEFFLER [2] found

$$(2.4) \quad I(\Theta) = \frac{I_0}{\pi\Theta_0^2} \exp [-\Theta^2/\Theta_0^2],$$

where the standard scattering angle Θ_0 is given by

$$(2.5) \quad (\Theta_0)^2 = 4\sqrt{\pi} \int \frac{(\Delta n)^2}{l} ds.$$

If Θ becomes large it should be replaced by $\sin \Theta$; for the sun this case does not seem important.

In the case of a homogeneous layer and when Θ is small (2.5) becomes

$$(2.6) \quad \Theta_0^2 = 4\sqrt{\pi} \frac{(\Delta n)^2}{b} s.$$

Since further

$$(2.7) \quad n^2 = 1 - e^2 N_e / \pi m f^2,$$

(f is the frequency in Hz), we have

$$(2.8) \quad \frac{(\Delta n)^2}{l} = \frac{0.19 \cdot 10^{16}}{f^4} \frac{(\Delta N_e)^2}{l},$$

so that

$$(2.9) \quad \Theta_0^2 = \frac{1.13 \cdot 10^{16}}{f^4} \frac{(\Delta N_e)^2}{l} s.$$

From a similar, earlier, treatment FEJER [3] found

$$\Theta_0^2 = \frac{\sqrt{\pi} \cdot \Delta \varepsilon^2 s}{l \varepsilon^2},$$

where ε is the dielectric constant. With $\varepsilon = n^2$, ε and $n \approx 1$ and $(dn)^2 = \frac{1}{4}(\delta\varepsilon)^2$. $\Theta_0^2 = 4\sqrt{\pi} (\Delta n)^2 s / l$ which is equal to (2.6).

Finally, CHANDRASEKHAR [4] applied a ray theory, which should be used when the phase deviation introduced by one irregularity is greater than one radian. He found an r.m.s. deflection of a ray given by $\Theta_0^2 = 2\sqrt{\pi} \Delta n^2 s / l$ which only differs by a factor 2 from the other results. We remark that $(\Delta n)^2$ and l cannot be determined separately; this is one of the great difficulties that are met in the scattering problem.

4. - Occultations of *Tau A*.

The annual occultations of the Crab nebula (*Tau A*) offer a beautiful opportunity to study the scattering in the outer parts of the solar corona. The main observational results may be summarized shortly as follows:

a) The angular diameter of the source, being of the order of some minutes of arc increases to some tens of minutes during the eclipse; the diameter is largest for the longest wavelength and closest to the sun.

b) No clear displacement of the source has been observed.

c) The brightness measurements give conflicting results. Observations of HEWISH (Cambridge) and VITKEVITCH (Crimea), made with two-elements interferometers at wavelengths between 190 and 790 cm show that the brightness of the source *decreases* during the eclipse, whereas observations at Nançay made with a 32 elements interferometer at $\lambda = 178$ cm show that the integrated brightness of the source *increases* during the eclipse.

In view of the conflicting results on the brightness measurements we discuss only the observations of the increase of the angular diameter.

Clearly Θ_0 is the angular diameter of a distant point source, when viewed through the corona. The discussion of the observations of the occultations of *Tau A* necessitates solving the integral equation (2.5), a procedure that may be approximated in view of our very imperfect knowledge of the outer corona. However, a procedure as that by HEWISH [5], approximating the corona at

a distance ϱ from the solar centre by a homogeneous layer with thickness ϱ , seems not wholly justified. SCHEFFLER [2] refined the treatment by performing the integration through a spherical corona and found that the assumption $(\Delta n^2/l) \sim \varrho^{-m-1}$ leads to $\Theta_0^2 \sim \varrho^m$, where ϱ is the projected distance to the solar centre expressed in solar radii. Some trials as to the form of the function $\Theta_0(\varrho)$ are shown in Fig. 9.

Clearly the linear approximation and the ϱ^{-3} -function represent the observations equally well but the ϱ^{-3} -function explains better the brightness distribution across the disk (Section 5).

5. - Scattering by an emitting layer: centre-limb variation of T_b .

The scattering by an emitting layer is much more complicated than the case discussed before: the spherical form of the corona, and the curved paths of non-scattered rays have to be taken into account. There are, however, no fundamental difficulties, and it appears moreover that only a rather narrow

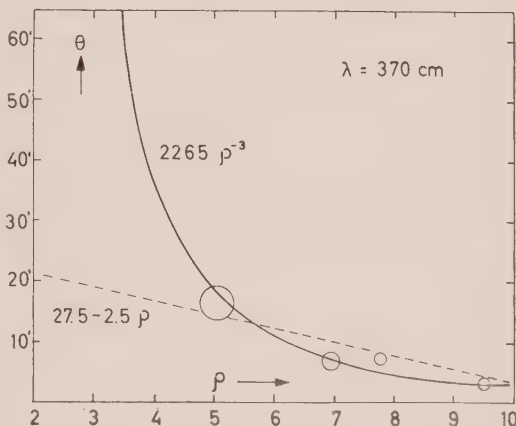


Fig. 9. Observed angular diameters of *Tau A* during the eclipses; $\lambda = 370$ cm. The observations are tentatively represented by a linear function and by a cubic one (SCHEFFLER [2]).

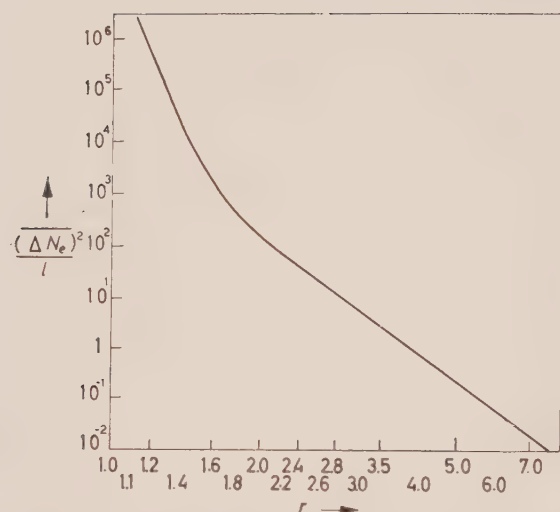
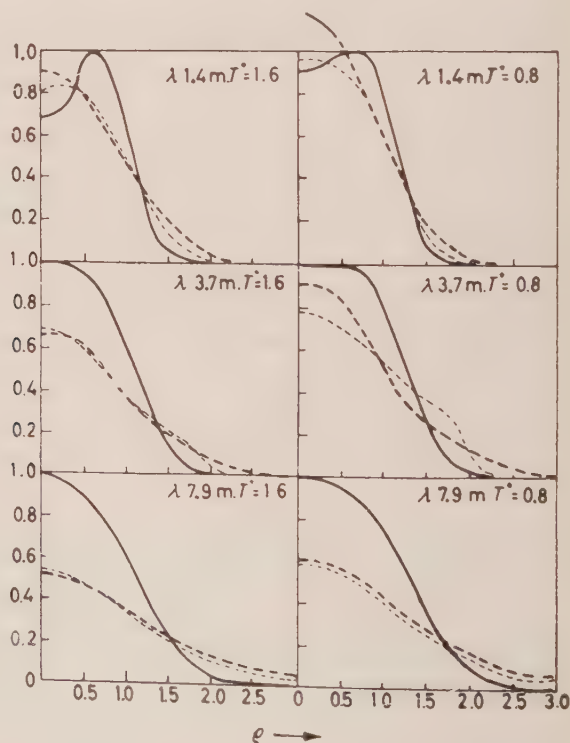


Fig. 10. — Variation of the function $(\Delta N_e)^2/l$ through the corona. This result has been found empirically by SCHEFFLER from a combined discussion of the increase of diameter of *Tau A* during its eclipses, and the solar radio-brightness distribution.

layer contributes effectively to the scattering because of the rapid decrease of density and of $(\Delta N_e)^2/l$ with height. We do not go into details but give

in Fig. 10 the function $(\Delta N_e)^2/l$ as it was found by SCHEFFLER by combining the observations of *Tau A* with centre-limb observations at metre-waves. Fig. 11 shows the computed centre-limb functions for the $\Delta N_e^2/l$ function of Fig. 10 and for assumed coronal temperatures of $1.6 \cdot 10^6$ °K and $0.8 \cdot 10^6$ °K.

Fig. 11. — Computed and observed brightness distributions of the sun at metre waves, all computed assuming a constant coronal temperature. --- Observations (O'BRIEN, 1953). — Computed without «scattering». ... Computed with «scattering». Lefthand figures: $T = 1.6 \cdot 10^6$ °K; right-hand: $T = 0.8 \cdot 10^6$ °K.



6. - Discussion: temperature of the corona and size of coronal irregularities.

First the temperatures. The best fit to the observations is obtained for $T_{\text{cor}} = 1.6 \cdot 10^6$ °K. Obviously, a good fit for a lower temperature could perhaps also have been obtained, by making another assumption on $\Delta N_e^2/l$, but nevertheless this result again poses the question of the coronal temperature. The kinetic properties of the corona (line widths, density decrease with height) indicate $T \approx 1.5 \cdot 10^6$ °K but the kinetic temperature determined from the ionization equilibrium of the ions, close to the surface, indicates rather $0.7 \cdot 10^6$ °K. The problem of the cross-section of the coronal ions is not yet wholly solved (cf. SCHWARZ [6], who found $T_{\text{e1}} = 2 \cdot 10^6$ °K from revised cross-sections).

Next we examine what information Fig. 10 can give on the diameters of the irregularities in the corona. Irregularities must be provided by a kind of turbulence. In a normal non-magnetic turbulence theory we would expect irregularities of the order of the scale height

$$H = RT/\mu g \approx 50\,000 \text{ km}.$$

In that case one would expect $\sqrt{\Delta N_e^2}/N_e$ to be of the order 0.4 through the whole corona (Fig. 12). Only in the low corona ($\rho < 1.4$) would we obtain relative density fluctuations exceeding unity, which does not seem well possible. Being given the uncertainty in the coronal $\log N_e$ values (p.e. ≈ 0.1 to 0.2), and the fact that we assumed the corona circularly symmetric in the present derivation, and further the uncertainties in the discussion of the irregularities, the present result may be an indication that inho-

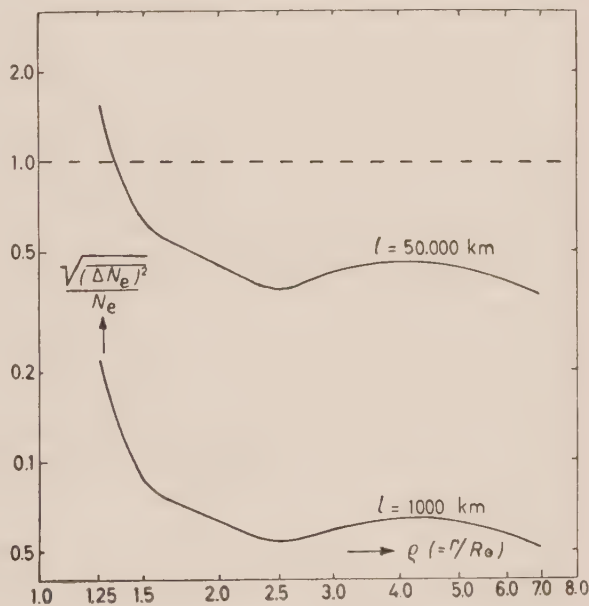


Fig. 12. - Variation of $\sqrt{\Delta N_e^2}/N_e$ through the corona for assumed values of 50 000 km and 1000 km for the scale l of the irregularities. For other values of l the curve is obtained from the given ones by a vertical shift equal to $\frac{1}{2} \Delta \log l$. The above results have been obtained by combining our Fig. 10 with the electron densities of the quiet minimum corona given in our Fig. 5 and in C. DE JAGER, [1], Table 17, p. 271.

mogeneities $\gg 10^5$ km are not likely to play an important role in the scattering of the *Tau A* radiation and in the smoothing of the solar brightness distribution.

But it seems very unlikely that we are dealing with real turbulence. The coronal density is so low ($\approx 10^{-16}$ g cm $^{-3}$) that even for turbulent velocities of the order of 100 km/s (which have never been observed) a magnetic field smaller than one gauss would suffice to keep the kinetic energy of the gas far above the turbulent energy. This fact and the observation that the whole corona is continuously streaming outwards and is replaced in a time interval of one day to one month (see Chapter III) make clear that we have to see the corona as an unstable dynamic feature in which the motions are to a large degree controlled by the magnetic fields. Classical «turbulence» is wholly inhibited in that case. Hydromagnetic theory should yield another relation between ΔN_c^2 and l , that could be combined with the one given in Fig. 10, in order to decide on the characteristic lengths and the density fluctuations in the corona. The problem of the shape of the inhomogeneities will be discussed in somewhat more detail in the next Chapter (III).

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III.

Spherical Asymmetry of the Quiet Radiosun.

There is a clear asymmetry in the solar radiobrightness distribution. Also the two-dimensional interferometric observations of the occultations of *Tau A* show an asymmetry.

1. - Two-dimensional interferometry of the Crab nebula.

The chief results obtained by HEWISH in 1956 and 1958 are shown in Fig. 13 [1]. This figure shows the sun and the approximate measured dimensions of the source *Tau A*. The dashed line, tentatively drawn in the 1958 graph is suggested to be a magnetic line of force emerging from the poles. The line

does not quite fit a dipole field; such lines would emerge more parallel to the sun's axis and would be less stretched. The suggested explanation for the asymmetry of *Tau A* during the occultation is that the radiation of the point source would be more scattered in a direction perpendicular to the lines of force than in the direction of the lines. This is in full agreement with what we know about the polar rays, which are surely connected with the solar magnetic field. The rays occur in the polar regions; their thickness at their basis is of the order 7 000 km, their width increases with increasing distance to the sun, concurrent with the divergence of the magnetic lines of force. At a distance of $0.2 R$ to the solar surface, where the rays are best visible their magnetic energy density greatly exceeds the kinetic

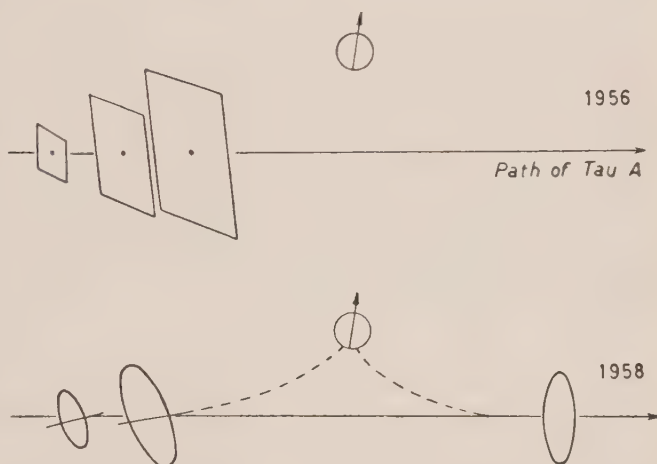


Fig. 15. — Approximate shape of *Tau A* in 1956 and 1958 during its passages behind the outer solar corona. Observations obtained at the Mullard Radio Observatory at Cambridge at a wavelength of 790 cm (HEWISH, [1]).

energy density of the thermal motions; so hydromagnetics should be applied. When somewhere a density maximum occurs, its sideward diffusion will be prevented by the magnetic field and the charged particles will chiefly escape in the direction of the field spiralling along the lines of force and pushed outwards by the divergence of the field. By subsequent evaporation this matter will, finally, disappear completely from the sun. The evaporation time has been estimated (BIERMANN [2], DE JAGER [3]) to be of the order of one day. We remember that also the polar plumes have a life-time of that order. So the polar rays show us how matter can escape from the polar regions of the sun. It is interesting to compare in this connection:

	Polar plumes	Coarse mottles of the chromosphere
Diametre	7 000 km	(5 000 ÷ 10 000) km
Life-time	between $\frac{1}{2}$ and one day	

This agreement might be accidental. However, since we now know that also the mottles are the seats of magnetic fields (cf. reference [4] to LEIGHTON's work in KIEPENHEUER's paper, p. 82), one may ask oneself whether the loss of mass and magnetism from the sun is not accompanied by the apparition of a bright mottle at the surface. It should, however, be added immediately that no clear relation has been found between the polar rays and the so called *polar faculae*, which, themselves have diameters of the order of 2 000 km and life-times of the order of half a day.

On the other hand one may pose the related question whether perhaps the increase of density in a solar *activity centre* is correlated with the increase of the number of bright coarse *K*-mottles. For the time being it seems tempting to assume a relation between the coarse mottles, a magnetic field, and the loss of matter by the sun. So our *hypothesis* is that *loss of matter by the sun will occur primarily in the coarse mottles*. But since we know that the coarse mottles are mostly composed of many smaller mottles, which, in turn have appeared to be identical with the spicules seen from above [4, 5] this hypothesis means that the loss of matter by the sun may be proportional to the number of low chromospheric spicules. This need not necessarily mean that spicules transport mass but it could also signify that the spicules are the main source for the heating of the corona: a high temperature causes a greater rate of evaporation.

The average density in the plumes has been estimated to be 5 to 9 times the density of the matter between. Hence the polar rays are to be considered as rays of gas escaping from the sun, guided by a magnetic field, in a nearly empty surroundings. For that reason one could expect that the *Tau A* source, when passing behind the corona should be occulted during the greater part of the time but also become wholly visible from time to time, without increase of the apparent diameter.

The number of rays behind which the source is occulted should in most cases be small; of the order of one to some.

2. The shape of the polar rays at great distances to the sun.

The direction of the inhomogeneities as indicated by the shape of *Tau A* (see Fig. 13) indicates that at great distances to the sun the polar rays do not fit a dipole field. This particular shape of the lines of force may be explained by considering that the coronal matter in the vicinity of the sun is subject to two forces: *a*) They are trapped in the solar magnetic field and tend to move to and fro from one pole to another, along the lines of force. *b*) Due to the high temperature the coronal gas tends to escape outwards.

In the vicinity of the sun the magnetic energy density of the gas exceeds

the thermal energy; so there the particles will tend to follow the lines of force. This explains why close to the sun the shape of the polar plumes does not differ much from that of a dipole field. However, the magnetic energy density decreases as ϱ^{-3} whereas the thermal energy density of an isothermal corona that continuously moves outwards decreases as ϱ^{-2} . So up from a certain point $E_{th} > E_{mag}$ so that at greater distances to the sun the matter tends to stream more and more in a radial direction, as indicated schematically in Fig. 14. This problem should be worked out quantitatively.

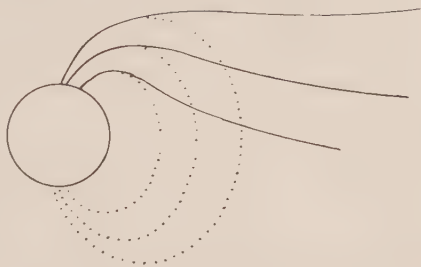


Fig. 14. Tentative explanation of the shape of the solar inhomogeneities at great distances to the sun. $\cdots$ Magnetic lines of force of a dipole field. $-$ Shape of filaments of gas under the influence of the magnetic field and the expanding motion of the corona.

3. - The pole-equator asymmetry in the brightness distribution.

Optical observations show that the polar electron density is less than the equatorial density by about a factor 2 (Fig. 5). This difference can not explain the observed radiobrightness distribution, where considerable differences occur between the poles and the equator. Adjusting the temperatures does not help either: the required polar temperatures would be much too low to be reconciled with optical observations (Fig. 6).

So, as another resource there remains the solution of «scattering». It looks quite probable that in the thin polar rays with their large density fluctuations ($\sqrt{\Delta N_c^2/N_c} \approx 1$) a great amount of scattering occurs into a direction parallel to the equator. Application of eq. (2.9) with adopted values $\Delta N_c = 10^7$, $l = 10^4$ km, $s = 5 \cdot 10^5$ km, $f = 10^8$ Hz, would yield $\Theta = 40^\circ$. In the present case of a self-emitting layer the actual scattering angle will be smaller than that but still considerable.

So it seems that the chief difference between the poles and the equator of the sun at radiowavelengths can be reduced to differences in the orientation of the scattering elements. Perhaps the equatorial elements are less filamentary than the polar plumes, a conclusion that seems also evident from a look at eclipse photographs of the corona.

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IV.

Radioemission from Centres of Activity.

The radioemission from a C.A. has been discussed by Drs. COUTREZ and WILD. We summarize shortly and give at the same time a qualitative explanation by referring to the Figs. 4 and 11 of a review paper to appear next year (DE JAGER [1]). In this chapter we discuss the thermal radioemission from a C.A.

1. - Review of large scale coronal features.

First we summarize our ideas on coronal features, for the sake of grater clarity.

	T (10^6 °K)	$\log N_e$ (cm^{-3})	H (gauss)	Average life-time
quiet corona	1 to 2	9 to 4	2	one day; 11 y. cycle in coronal densities
coronal activity regions	2	2 to $10 \times$ $\times$ quiet corona	$10 \div 100$	weeks to months
coronal condensations	≈ 4	10 to $20 \times$ $\times$ quiet corona	?	some days
« hot spot » in coronal condensations	$5 \div 10$	?	?	20^m to 2^h

It is highly desirable clearly to distinguish between the normal corona activity regions and the coronal condensations. The first are the regions of slightly enhanced density that occur above a C.A. The coronal condensations

are somewhat smaller, have a much higher density than the surrounding quiet corona, and also a higher temperature, and live only for some days. « Hot spots » in the coronal condensations are correlated to the occurrence of flares and live very shortly. Their temperatures must be high.

The term « condensation » might easily lead to a misinterpretation; obviously nothing condenses in the corona. It would perhaps be better to speak of « densification ». In the following part this latter term will be used sometimes by us, but in most cases we shall keep to the classical term: condensation.

2. — Thermal radioradiation of a C.A.

We compare the optical and the radio-observations of a C.A.

a) Coronagraphic observations show a brightening of the 5303 Å line (Fe XIV, 255 eV) at the same place as the facular field. The red line (6374 Å; Fe X; 233 eV) is sometimes bright also above these regions but it is often bright at the sides of them. The increase in brightness of the 5303 Å line suggests that the line is at the maximum of its ionization in the C.A.'s, which would yield an electron temperature of 1 to $2 \cdot 10^6$ °K. These regions often show many fairly stable ray and arch structures, about 150 000 km long, often curved, radiating away from the C.A. They tend to expand gradually in the course of hours. Occasionally more rapid motions occur in them.

b) High-resolution radio-observations at cm and dm waves show enhancements that coincide with facular fields. The spectrum of a typical coronal C.A. shows a relative maximum in the region of dm waves (Fig. 15). At 22 cm these activity centres show brightness temperatures up to $1.5 \cdot 10^6$ °K, (the common value being $6 \cdot 10^5$ °K (CHRISTIANSEN and MATHEWSON, 1959)), whereas the brightness temperature of the undisturbed sun at 22 cm is 55 000 °K. Such a great increase in brightness cannot be explained by the small increase in temperature suggested by the observation of the green coronal line but rather suggests an increase of the density.

Roughly this may be shown as follows. The absorption coefficient of radio radiation, κ is proportional to $N_e^2 T_{ei}^{-\frac{3}{2}}$, whereas the emission of radiation B in the radiorange is proportional to T_e , so that the ergiebigkeit $\sim \kappa B \sim N_e^2 T_{ei}^{-\frac{1}{2}}$. An increase of T_{ei} would thus give a decrease of radiation unless compensated by an increase of N_e .

Application to the case of the 22 cm radiation observations yields that $(N_{e \text{ C.A.}}/N_{e \text{ quiet sun}})^2 \approx 1500\,000/55\,000 = 25$ (since the influence of T_{ei} is virtually negligible); hence $N_{e \text{ C.A.}}/N_{e \text{ quiet sun}} \approx 5$. For the average C.A.: $N_{e \text{ C.A.}}/N_{e \text{ quiet sun}} \approx \sqrt{11} = 3.5$. This reasoning is only valid as a first approximation. In a more detailed discussion one should take into account that an increase of den-

sity throughout the corona causes an increase of the optical depth $\tau_\lambda = \int \kappa_\lambda dh$ and so the centre of gravity of the emergent radiation shifts upward. This causes an increase of the brightness temperature in the region of enhanced density and a reduction of κ_λ . The essential point is that the corona, being transparent for $\lambda = 22$ cm when undisturbed becomes optically thick for that radiation in C.A.'s. If we assume the corona to be isothermal, then any density increase at metre-waves (where the corona is optically thick) will not produce the slightest increase of brightness temperature. As an example we give in

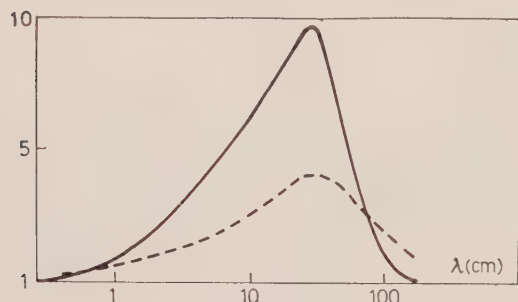


Fig. 15. — Solid line: Intensity ratio between a C.A. and the undisturbed sun, as a function of the wavelength (cm). Dashed: computed ratio for a C.A. with twice the coronal density.

Fig. 15 the brightness temperature for a coronal activity region assumed to have the same temperature as the quiet corona but a twice greater density. This curve also suggests that the coronal activity regions have a density greater than that of the neighbouring quiet corona by a factor ≈ 5 . In this connection it may be useful to remark that the often used expression cannot be correct, that the coronal activity regions at radiowaves do not

extend higher than, say, 100 000 km, and that higher up no deviating N_e values should occur because no increase of the brightness temperature is observed at metre-waves. At metre-waves a density increase does not manifest itself in the emergent radiation, if the corona is isothermal. Only T -variations can be discovered.

So the *coronal activity region* presents itself as a region of slightly higher temperature and of considerably greater density (average: 5 times) than the normal corona. The projected area of the coronal C.A. is about equal to that of the faculae. Since an increase in the brightness temperature is only sometimes observed at short metre-waves ($\lambda \approx 1$ m), and during a short time, the region of increased temperature does not extend much higher than about 10^5 km. The enhanced density region *can* extend further, but it should be discovered by other means.

A *permanent coronal condensation* may live for some days, often in connection with the largest, so called *F*-type spot groups. It shows the Ca XV line $5694 \text{ \AA}$ (excitation potential 814 eV) and sometimes also a bright continuous spectrum, indicating N_e -values of 0.5 to $2 \cdot 10^{10} \text{ cm}^{-3}$, ten to twenty times the values for the quiet corona. They are semi-spherical or elliptic. Line profiles indicate temperatures of the order of 2 to $5 \cdot 10^5 \text{ }^\circ\text{K}$.

From radio-observations at 3 cm KUNDU [2] found that the occurrence of flares in a C.A. is often connected with a radio « hot spot », with a diameter smaller than 75 000 km and with a brightness temperature of $5 \cdot 10^5$ °K (the brightness temperature of the quiet sun at that wavelength is 15 000°). Probably this is also a consequence of the greatly increased density in a permanent coronal condensation.

3. — Bright spots at long wavelengths.

It has been found that at 88 cm and at 178 cm sometimes also brightness maxima occur, which do not coincide with activity centres. This behaviour could be explained (WALDMEIER; discussion remark at Paris Symposium on Radio Astronomy [3]) by

remembering that a C.A. has a finite extension but that it is often surrounded by filaments, occurring themselves in a dark « dome », above which one often observes an enhanced density (coronal rays). So we should get the following picture (Fig. 16).

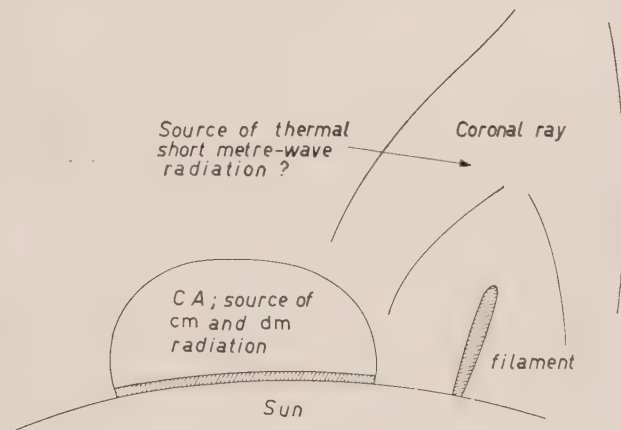


Fig. 16.

4. — Centimeter bursts.

The observations show the greater part (90 %) of the cm bursts for $\lambda < 20$ cm to be rather smooth, at variance with the bursts emitted at metre-waves. Often the tail part seems to decay exponentially with a decay time of 10 to 20 min. Their top intensities are of the same order as the quiet-sun level. About half of them show circular polarization. The hypothesis that most of these bursts are caused by thermal radiation emitted by the flare regions or the regions just above them is supported by:

- 1) Their decay times, being of the same order as that of the flares;
- 2) the relative low top intensities;
- 3) their small diameters ($\approx 1'$);
- 4) the observation that many cm bursts coincide with a flare;
- 5) the fact that the solar cm radiation is emitted by the same height levels where the flares tend to occur.

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V.

The Emission of Radio Bursts.**1. – Introduction.**

The observations show that a number of type II and type III bursts show harmonics. These bursts might be excited by non-linear oscillations of the coronal plasma. This hypothesis will be confirmed if *a*) it could be possible to prove experimentally that the bursts of a certain frequency emerge from a level, roughly identical to the level where plasma oscillations of that frequency can occur, and *b*) if a theory could be given of the excitation of electromagnetic radiation by plasma oscillation in the corona. The first point has been proved by the Australians (see J. P. WILD's lectures). We are here only concerned with the second point. We shall discuss:

- | | |
|--|-------------|
| <i>a</i>) The origin of the high velocities; | Chapter V |
| <i>b</i>) Excitation of plasma oscillations; | |
| <i>c</i>) Emission and damping of radiation of
individual electrons; profiles; | Chapter VI |
| <i>d</i>) Collective phenomena; | |
| <i>e</i>) Radiation by plasma oscillations. | Chapter VII |

2. – The origin of high velocities.

No acceptable mechanism has as yet been advanced, able to produce material velocities of the order of 10^5 km/s, but there are some mechanisms that can produce velocities up to 10^3 km/s, which is the order of the greatest material velocity, observed as yet (the velocities of type III bursts might not be due to particle motion but also to a displacement of an excitation). We should remember that flares, and the associated high velocity puffs and sprays occur as a rule in complicated field regions, hardly in unipolar spots, more in bipolar ones and often in irregular spot groups. They seem related to changes in the

field strengths of the spots: a change of the magnetic field will induce an electrical field. If moreover the region where the induction takes place is virtually neutral this might lead to the observed accelerations. The induction law is written for that purpose as

$$(5.1) \quad \oint \mathbf{E} ds = -\frac{1}{c} \left| \frac{\partial}{\partial t} \right| \int \mathbf{H} d\Sigma,$$

where s is the circumference of the area Σ . We introduce a characteristic length λ and a characteristic velocity V , then (5.1) may be written as

$$E\lambda \approx \left| \frac{Hv\lambda}{c} \right| \quad \text{or} \quad E_{\text{ind}} \approx \frac{Hv}{c} \text{ c.g.s.} = H \cdot v \cdot 10^{-8} \text{ V cm}^{-1}.$$

For H we take 1000 gauss and for v , 0.1 km/s, the observed average displacement of a sunspot. Then $E_{\text{ind}} \approx 10^{-1} \text{ V cm}^{-1}$. It may be correct to assume that flares occur only if the field changes are quicker than normal. In that case one might obtain $E_{\text{ind}} \approx 1 \text{ V cm}^{-1}$.

The next point is that the acceleration can only take place if the magnetic field itself is small ($|dH/dt|$ being large). This seems to be confirmed by observations of SEVERNY and associates, who showed that flares occur often in neutral regions.

Next we ask for the region over which the acceleration can take place. It seems to the present author that on the average this region should be of the same order as the so called «electromagnetic shielding distance», *i.e.* a distance such that the magnetic field due to the induced currents affects the original field appreciably; or, otherwise stated: a distance such that the electric field $(1/c)\mathbf{v} \wedge \mathbf{H}$ is balanced by the electric field due to changes in the magnetic field [1]. An expression for this distance can easily be derived.

Any motion of a mass of gas in a magnetic field will induce another magnetic field according to

$$(5.2a) \quad \text{curl } \mathbf{H}_{\text{ind}} = \frac{4\pi}{c} \sigma \mathbf{E} = \frac{4\pi}{c^2} \sigma \mathbf{v} \wedge \mathbf{H}.$$

We ask that the mass of gas be so great that $H_{\text{ind}} \approx H$. Hence, remembering that $[\text{curl}] = [l^{-1}]$, and introducing the order of magnitude quantity λ_s , per definition equal to the shielding distance, (5.2a) yields

$$(5.2b) \quad \lambda_s = c^2/4\pi\sigma v.$$

Now, in a flare $\log \sigma \approx 13$ [2], hence $\lambda_s \approx 10^4 \text{ cm}$. This small distance is sufficient to set up a potential difference of 1000 V (for an assumed velocity

$v = 1$ km/s) or 10 000 V (for $v = 10$ km/s). These fields could accelerate charged particles to the following velocities:

	electrons	protons
1 000 V	20 000 km/s	450 km/s
10 000 V	60 000 km/s	1 350 km/s

Although the values in the last row of this Table are not exactly equal to the observed average velocities of type II and type III bursts (1500 and 150 000 km/s respectively) they are close enough to these values to make necessary to examine the question whether these two types of bursts are perhaps due to electrons and protons accelerated in a part of a flare where dH/dt is large, and $H \approx 0$.

First a short remark on the shielding distance introduced above. Of course this quantity represents only an order of magnitude. Deviating values of a factor 10 or even much more can easily be realized in the sun, depending on the local electromagnetic and velocity fields; cf. also [3].

It is even possible to construct field configurations so, that in one direction the distance over which acceleration can take place is perhaps a hundred times the shielding distance. It seems, however, very improbable to the present author that in the sun fields can be realized such that the acceleration can take place over distances of the order of 10^9 cm, as assumed in Kiepenheuer's contribution. In order to reach acceleration distances of that length, a rather artificial situation should locally be created. Nevertheless, a field of 10^5 V which could accelerate electrons to 165 000 km/s does not seem improbable to us. It could be realized by an acceleration over one km, with a potential difference of 1 V/cm.

The problem whether charged clouds of particles can move through a plasma without being immediately stopped by electric attraction has not yet been investigated for the special case, discussed here.

Semi-qualitatively one may argue as follows. For velocities, as large as those described above, the collision cross-section of the particles becomes very small; the free path of the particles becomes much longer than the solar diameter. Hence, there will be only very little interaction between any of the particles of the moving cloud of electrons or protons and the surrounding coronal gas. As soon as—say—a cloud of electrons is accelerated and moves through the corona, the cloud will disperse because of the mutual repulsion of the particles. This repulsive force will no longer have influence when the average mutual distance of the particles becomes greater than the Debye distance,

$$h = 6.90 (T/N_e)^{\frac{1}{2}},$$

being a measure for the distance over which deviations from the neutrality of the gas can be perceived, or, otherwise said: the distance over which the field of one particle is not yet shielded by the surroundings. In the inner corona ($T = 10^6$ °K, $N_e = 10^8$) $h \approx 1$ cm but more outwards h becomes greater proportional to $N_e^{-\frac{1}{2}}$, leading to a further expansion of the cloud.

This could perhaps be the reason why type III and type II bursts are some times followed by type V and IV bursts, which are caused by disperded clouds of energetic particles at large distances to the sun.

We do not go in further detail but want to remark that here is a problem that perhaps merits to be investigated.

Let us further remark that the acceleration mechanism, described here, and based on electromagnetic fields, can only be effective in the flares, or in a prominence; in the corona, where σ is 10^4 times greater than in a flare or prominence, no appreciable acceleration can be expected.

In the next sections we describe some alternative aspects of the acceleration problem. Some further arguments that type III bursts are perhaps due to streams of fast electrons are given in [3] and [4].

3. — The velocities of type II and type III bursts.

The type II and III bursts have average velocities of 1500 and 150 000 km/s. These could be attained by means of mechanism as described above; for their explanation some alternative suggestions have also been given. WESTFOLD [5] has given some arguments to show that the type II velocities might be associated with the shock velocities of corpuscular streams having velocities of the order of 1000 km/s, and that the type III velocities might be associated with a magnetohydrodynamic component in the sound velocities, in a strong magnetic field. So it should not be the corpuscular velocity but rather the associated shock and Alfvén-velocities that produce the observed bursts.

3.1. The type II bursts explained by shock-waves. — A shock front is a discontinuity surface; shocks originate *e.g.* when a piston moves through a gas not necessarily with a supersonic velocity. Strong shocks originate when piston velocities $> v_{\text{sound}}$ are considered. The mathematical expressions regarding shocks are obtained by writing down the equations of conservation of mass, momentum, and energy before and behind the front. Working out shows that the enthalpy ($i = e + p/\rho$, where e is the internal energy) of a shock increases by the work done by the pressure to the average volume. We do not discuss in detail the shock relations [6], but give the formula, expressing the shock velocity V ahead of a stream of particles moving with velocity v

into a medium where the sound velocity is v_s :

$$(5.3) \quad V = \frac{2}{3} v_1 + \left(\frac{4}{9} v_1^2 + v_s^2 \right)^{\frac{1}{2}}$$

In the corona the sound velocity is $v_s = \sqrt{\gamma P/\bar{\rho}} = 170$ km/s. Then the shock velocity associated with a corpuscular stream moving with 1000 km/s would be 1500 km/s. So in order to predict the type II bursts we need at least corpuscular velocities of 1000 km/s; such velocities are sometimes observed optically.

3.2. *The type III bursts explained by transverse Alfvén waves.* — Alfvén waves originate when motions occur in a plasma where the lines of force are frozen into the matter. The conditions for having « frozen-in » fields is that the diffusion time of matter with respect to the lines of force is small as compared to the characteristic time for the system. This condition may be derived as follows:

We start with the current equation

$$(5.4) \quad \mathbf{j} = \sigma \left(\mathbf{E} + \frac{1}{c} \mathbf{v} \wedge \mathbf{H} \right)$$

and since

$$(5.5) \quad \text{curl } \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{H}}{\partial t},$$

we obtain from (5.4) and (5.5)

$$(5.6) \quad \frac{\partial \mathbf{H}}{\partial t} = \frac{1}{\sigma} \text{curl } (\mathbf{v} \wedge \mathbf{H}) - \frac{c}{\sigma} \text{curl } \mathbf{j}.$$

Further

$$(5.7) \quad \text{curl } \mathbf{H} = \frac{4\pi}{c} \mathbf{j},$$

$$(5.8) \quad \text{div } \mathbf{H} = 0.$$

Combining (5.6), (5.7) and (5.8) yields

$$(5.9) \quad \frac{\partial \mathbf{H}}{\partial t} = \frac{1}{c} \text{curl } (\mathbf{v} \wedge \mathbf{H}) + \frac{c^2}{4\pi\sigma} \nabla^2 \mathbf{H}.$$

By introducing order-of-magnitude quantities τ (time) and λ (distance) eq. (5.9) becomes

$$(5.10) \quad \frac{H}{\tau} = \frac{vH}{\sigma\lambda} + \frac{c^2}{4\pi\sigma} \frac{H}{\lambda^2}.$$

In most astrophysical cases $vH/\sigma\lambda \ll (c^2/4\pi\sigma)H/\lambda^2$, and then (5.10) becomes

$$(5.11) \quad \tau = 4\pi\sigma\lambda^2/c^2.$$

In the sun we have the following characteristic times:

	photosphere	sunspots	spicules	prominences	corona
λ (cm)	$2 \cdot 10^7$	$2 \cdot 10^9$	10^8	$5 \cdot 10^8$	$5 \cdot 10^9$
$\log \sigma$	12	10	13.5	12	16
τ (s)	$4 \cdot 10^6$	$2 \cdot 10^8$	$3 \cdot 10^8$	$3 \cdot 10^8$	$2 \cdot 10^{15}$

In all cases τ is so large that we are certain to deal with frozen-in fields. However, the photosphere and the upper parts of the sunspots are mainly neutral; in that part of the sun Alfvén waves play only a little role in determining its dynamic state. However, any material motion in the other parts of the sun will have the character of hydrodynamic (Alfvén) waves, in which

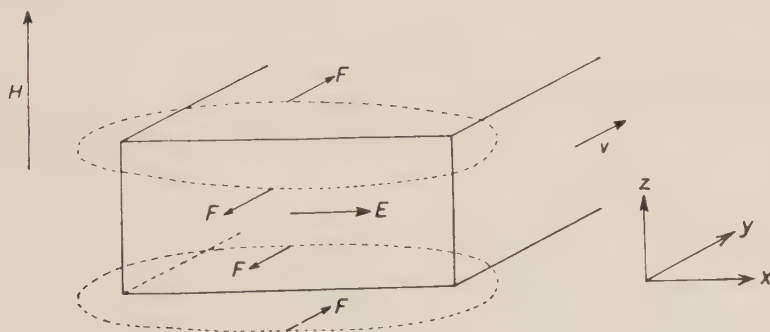


Fig. 17.

oscillations of matter and of the magnetic field occur simultaneously, and propagate with the velocity

$$v_A = H(4\pi\rho)^{-\frac{1}{2}}.$$

The origin of the Alfvén waves can be made acceptable in the following qualitative way, after Alfvén (cf. also [7]). Let an infinitely long, piece of plasma, rectangular in the x - z plane, be moved into the y -direction (cf. Fig. 17).

The magnetic field is parallel to the z -axis. Then an electric current $\mathbf{j} = (\sigma/c)\mathbf{v} \wedge \mathbf{H}$ will be induced; it has the direction of the positive x -axis. A current system will flow along the dashed closed lines. Because of the magnetic field $\mathbf{H}$ forces $\mathbf{F} - (1/c)\mathbf{j} \wedge \mathbf{H}$ originate which are into the direction of the negative y -axis in the shifted piece of matter, and into the positive direction above and below this piece. So two *transverse* oscillating motions originate containing both a variable $\mathbf{v}$ and a variable $\mathbf{H}$ component, propagating up and downwards in a direction parallel to the fields. The period and amplitude of these oscillations is solely determined by the initial disturbance.

There is, however, also a *longitudinal* mode of propagation, perpendicular to the field, which is less well known (DE HOFFMAN and TELLER [8]; VAN DE HULST [9]; WESTFOLD [5]). This wave is similar to sound waves and originates from the Alfvén waves because of the compression of the matter and of the field, so that there is an additional influence of the magnetic pressure.

In the absence of a field the velocity of sound is

$$v_s = (\gamma P/\varrho)^{\frac{1}{2}}; \quad \gamma = (d \log P / d \log \varrho)_{ax} = \frac{5}{3},$$

in an ionized gas. Since the magnetic pressure $H^2/8\pi \sim \varrho^2$ we have $\gamma_{\text{magn}} = 2$. The velocity of propagation of these hydromagnetic (longitudinal) waves can then be computed in quite an analogous way as that of ordinary sound waves (cf. e.g. WESTFOLD [5]). Only a term for the magnetic energy is added to the equation for the conservation of energy. One then obtains that the speed of propagation is given by

$$(5.12) \quad v_s'^2 = v_s^2 + v_A^2.$$

For large fields $v_s' \approx v_A$. In the solar corona $v_A = 220 H$ km/s, and $v_s \approx 170$ km/s. So, if $H_0 = 1000$ G, $v_A = 2 \cdot 10^5$ km/s. For that reason WESTFOLD assumed that the type III velocities might be identified with the hydromagnetic shock velocities ahead of a particle beam moving at much slower speed. The problem is whether such high magnetic fields can occur in the corona. For the time being there are no direct indications in that direction. We know however, that sometimes prominences, which are shot upwards keep their forms fairly well, without increasing greatly in size, even if the surrounding density decreases by a factor of 100 or more. So, the force which keeps the prominence together, presumably a magnetic field is transported upward without much loss of strength. Similarly one could imagine that stronger fields are brought upwards.

Another argument that strong magnetic fields are sometimes brought up into the corona is given by the type IV bursts. TAKAKURA [10] has shown that the life-times of these bursts can only be understood if it is assumed that they are emitted by a cloud of gas having a magnetic field of the order of some 300 gauss. Presumably this field must have been brought upwards.

4. – Summary: high velocities from flare regions.

We summarize the way in which the high velocities observed in type II and III bursts might obtained.

1) A flare may start by a compression of the magnetic field region, probably by the mutual approach of two regions of different polarity. The coronal matter between the two regions thus gets compressed.

2) This compression, once ignited, may continue, perhaps by the mechanism described by Prof. KIEPENHEUER in his last lecture.

3) As SEVERNY has made acceptable, this compression stops only when the velocity of compression reaches the velocity of sound (≈ 170 km/s in the corona; ≈ 20 km/s in a common flare), so that shock waves originate. Then the flare may have obtained a density of about $2 \cdot 10^{13}$ electrons cm^{-3} .

4) At that time the conductivity in the flare is decreased to values about 10^4 times smaller than in the corona. The electromagnetic shielding distance increases to a value of about 100 m; protons can be accelerated to velocities of thousand km/s, electrons to values of the order 10^5 km/s. It is suggested that these streams cause the type II and type III bursts.

5) Alternatively one may consider that the shock velocities associated with a stream of particles of 10^4 km/s may be of the order of velocities of type II bursts.

6) In the corona these streams of particles may generate (longitudinal) hydromagnetic sound waves propagating with $v \approx 2 \cdot 10^5$ km/s if the local magnetic strength is of the order of 1000 gauss.

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VI.

Emission of Radiowaves by Plasma oscillations.

The discussion found in this chapter and the next differs in one essential point from that given usually. We stress that the sum of the individual emissions of the oscillating electrons will produce a sufficient intensity of radiation to explain the observed bursts. (This point of view has been expressed for the first time by FOKKER [1]) Of course, the plasma oscillations are collective phenomena, but it seems that these collective motions hardly yield any excess of radiation over the sum of the contributions of the individual oscillating electrons.

1. - Plasma oscillations.

Periodical oscillations originate in a plasma at the place where a space charge occurs. Let the electrons and the ions be displaced with respect to each other over a vector $\mathbf{s}$, then the space charge is

$$(6.1) \quad \varrho_e = \text{div} (e N_e \mathbf{s}) .$$

This yields an electric field according to

$$(6.2) \quad \text{div} \mathbf{E} = 4\pi\varrho_e .$$

Combining (6.1) and (6.2)

$$(6.3) \quad \mathbf{E} = 4\pi e N_e \mathbf{s} .$$

For a displacement $\mathbf{s}$ a force $-e\mathbf{E}$ will be imparted to each electron, so that oscillations occur according to

$$(6.4) \quad m \frac{d^2 \mathbf{s}}{dt^2} = -4\pi e^2 N_e \mathbf{s} .$$

The frequency of these oscillations is the plasma frequency:

$$f_0 = (e^2 N_e / \pi m)^{\frac{1}{2}} = 8.98 \cdot 10^{-3} \sqrt{N_e} \text{ MHz} .$$

The first problem to be solved is how space charge separation can occur.

2. – The origin of space charge separation.

It looks probable that space charge separation will occur in the case of very high velocities. If these occur in a magnetic field where particles stream with a speed v as compared to the surroundings, an electric field $E = v \cdot H \cdot 10^{-8}$ V/cm will be induced. For $v = 1000$ km/s and $H = 10$ G: $E = 10$ V/cm. The character of these separations and the question whether they will set up oscillations has not yet been discussed.

If there is no magnetic field a considerable space charge separation can also occur [2] when the speed of motion is of the same order or greater than the so-called « electron sound velocity »,

$$v_e = (5kT/3m_e)^{\frac{1}{2}} = 5.0 \cdot 10^5 \sqrt{T} \text{ cm/s.}$$

In the corona $v_e = 5000$ km/s. In that case the corresponding electrostatic potential differences are of the order of 10^4 or 10^5 V.

Finally PIDDINGTON [3] has shown that Alfvén waves of sufficiently high frequency lead to space charge separation, thus producing plasma oscillations. There is a continuous transition between Alfvén waves and plasma oscillations.

We will assume in the following that space charge separation does occur. Space charge separation automatically leads to plasma oscillations and so the next problem is whether these oscillations can lead to the emission of electromagnetic radiation.

First, however, before discussing the collective phenomena, we will discuss the radiation properties of singly oscillating electrons. In the next chapter the collective phenomena will be treated.

3. – Emission of radiation of the linear harmonic oscillator.

We review the classical Hertz theory (cf. *e.g.* A. UNSÖLD [4], p. 12). An electron, mass m and charge e oscillates with a frequency f_0 in the x direction. Neglecting radiation the equation of motion is

$$(6.5) \quad \ddot{x} + (2\pi f_0)^2 x = 0,$$

yielding the solution

$$(6.6) \quad x = A \exp [2\pi i f_0 t],$$

where A is real and where we should take the real part of the exponential.

Next we consider the emission of the radiation. Since the oscillating electron is continuously accelerated it will continuously emit radiation, at a rate

$$(6.7) \quad \frac{dE}{dt} = -\frac{2e^2}{3c^3} (\ddot{x})^2.$$

To incorporate this in the equation (6.5) we consider it as a friction force:

$$(6.8) \quad K = \frac{2e^2}{3c^3} \ddot{x},$$

because the time average of $K\dot{x}$ is equal to

$$\frac{2e^2}{3c^3} \ddot{x}\dot{x} = \frac{2e^2}{3c^3} \left[\frac{d}{dt} (\ddot{x}, \dot{x}) - \ddot{x}^2 \right] = -\frac{2e^2}{3c^3} \ddot{x}^2.$$

So the equation of motion becomes

$$(6.9) \quad \ddot{x} + (2\pi f_0)^2 x - \frac{2e^2}{3mc^3} \ddot{x} = 0.$$

It will be shown that damping is rather weak, so we may put, according to (6.5): $\ddot{x} = -(2\pi f_0)^2 \dot{x}$. Hence (6.9) becomes

$$(6.10) \quad \ddot{x} + (2\pi f_0)^2 x + \gamma \dot{x} = 0, \quad \text{with} \quad \gamma = \frac{8\pi^2 e^2 f_0^2}{3mc^3}.$$

The solution is

$$(6.11) \quad x = |A| \exp \left\{ -\frac{\gamma}{2} t \right\} \cos (2\pi f_0 t + \delta).$$

Here δ is an arbitrary phase-shift and γ proves to be the well-known damping constant for radiation damping. The damping time $T = 1/\gamma = \lambda^2/0.22$ is about 10^{-8} s in the optical region but it ranges from 5 to $5 \cdot 10^6$ s for wavelengths of 1 cm to 10 m. So, if the oscillator could radiate undisturbedly in the radio-range it would do this for a considerable time.

4. - Collisional damping.

The oscillator will not radiate as long as computed above, because of the influence of collisions with other particles, mainly with electrons. Collisions with ions occur less often because of their lower velocity; although the cross-section is larger the electrons still contribute more.

If the probability of one disturbing collisions is λ (s^{-1}), then the average intensity of radiation emitted by a volume containing a great number of oscillators will decrease as $\exp[-\lambda t]$ provided that λ is small as compared with the radiation damping constant computed above, and provided that the oscillators do not obtain new impulses. In computing the average collision time between charged particles the passage is generally considered to be a collision when the angle between the original and the deflected orbit differs by 90° or more. The deflection is then computed, given the charge of the particles z , their velocity v and the collision parameter b (b being the distance of closest approach if the particles would have kept moving along straight lines). Then the probability for a deflection $> 90^\circ$ is computed as a function of Z and v and by integrating over b . Here again, as in the case of the computation of the continuous absorption coefficient, divergencies would occur if b would be permitted to go to infinity. For the upper limit of the integration one usually takes the Debye distance h . Usually it is assumed that only collisions with electrons are important but WESTFOLD [5] showed that in the case of the solar atmosphere the incorporation of the influence of ions increases the collisional frequency roughly with $\frac{1}{3}$. Among the various expressions derived we might mention the one derived last year here in Varenna by FERRARO [6]:

$$(6.12a) \quad \lambda = Z^2 N_e \log a / 0.21 T^{\frac{3}{2}} \text{ s}^{-1},$$

where $\log a$ is a slowly varying function of N_e and T ,

$$a = \left(\frac{kT}{4\pi N_e e^2} \right)^{\frac{1}{2}} \frac{3kT}{Ze^2}.$$

Often Cowling's expression is used [7]:

$$(6.12b) \quad \lambda = 15 N_e Z T^{-\frac{3}{2}}.$$

For $N_e = 10^8$ and $T = 10^6$ °K these values differ by a factor 10, they are 20 and 2 respectively.

5. – The influence of the Doppler effect on the profiles.

We still consider a gas in which a number of oscillating electrons occur, not necessarily oscillating coherently but all oscillating with the same frequency. Each of these electrons will also have its thermal velocity so that the resulting motion will be a periodical one superposed on the linear motion. Consequently the frequencies of the radiation observed by a stationary ob-

server will be distributed around the mean frequency according to a Gaussian distribution, corresponding to the distribution of sightline velocity components in a gas with a Maxwellian velocity distribution (DE JAGER [8]; DE JAGER VAN'T VEER and SEEGER [9]). This suggestion would explain the bandwidth of many bursts.

for stormbursts we have [DE JAGER ⁽¹⁰⁾]:		derived T_{el} (°K)
at 100 MHz	$f = 4$ MHz	$1.7 \cdot 10^6$
160	5	$1.1 \cdot 10^6$
200	4	$0.45 \cdot 10^6$
400	7	$0.34 \cdot 10^6$

These temperatures are derived assuming that the widths of the profiles are the Doppler widths: $\Delta f = 2.26 \cdot 10^{-5} \cdot f \sqrt{T}$.

If, however, the radiation is emitted at the plasma frequency $\omega = \infty$ at $f = f_0$, that part of the line with $f < f_0$ will not be emitted, the part close to f_0 will be greatly attenuated so that roughly the line will get a width, perhaps half the Doppler width. The derived temperatures should then be greater by a factor $\sqrt{2}$, which still makes them well acceptable.

6. - Profiles of type III bursts.

When considering the profiles of bursts whose emission is excited by moving disturbances, like type II and type III bursts we have to take into account:

a) The frequency $f(t)$ excited at a time t is given by

$$(6.13) \quad f(t) = f' - at;$$

where f' is the frequency at which the observations are made. The linear approximation is permissible for a small frequency range.

b) The radiation intensity of each excited volume element will decay exponentially with the decay constant λ .

c) The radiation emitted by a particular volume element will be smeared out according to a Doppler profile. To avoid the difficulty of the great attenuation near the plasma frequency we assume provisionally that we are dealing with the second harmonics. It can then be shown (DE JAGER *et al.* [9]) that the observed profile can be written as

$$(6.14) \quad I_{\nu}(t) = \text{const} \exp [-\lambda t] (1 \pm \Phi(|Y|)),$$

where Φ is the error function, $Y = (at/\Delta) + (\lambda\Delta/2a)$; Δ is the Doppler width. The positive sign is for $Y > 0$, the negative for $Y < 0$.

Of a burst observed at a certain frequency we know the electron density (= plasma frequency density or $1/\sqrt{2}$ times this value). Then the profile of the burst has to yield us the values of a and of T .

It has been tried to apply this theory to some bursts observed at 200 MHz with reasonably good results (Fig. 18). The values of T range between 2.6 and $7.0 \cdot 10^6$ °K and those of a between 18 and 27 MHz/s. These results agree with observations of type III bursts.

Summarizing, we think that the forms of the profiles of the type III bursts can perhaps be explained by assuming that they are emitted by electrons, oscillating with the plasma frequency, widened by the Doppler effect and damped by collisions with other particles, mostly electrons.

We did not yet examine whether the observed intensities can also be explained by this mechanism. This comes in the next chapter.

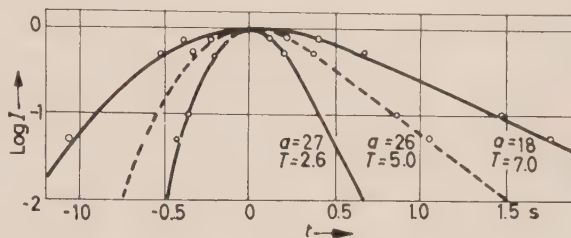


Fig. 18. — Observed profiles of radiopips at 150 cm (dashes), compared with computations (solid lines). The profile parameters a (MHz/s) and T (10^6 °K) are specified by the numbers on each profile (DE JAGER *et al.*, [9]).

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VII.

Collective Phenomena.

1. - The necessity of having plasma oscillations.

In the preceding chapter we considered the radiation of oscillating electrons and we computed the profiles of the bursts. We did, however, not compute the expected intensity of the emitted radiation. This will be done here, following FOKKER [1]. We assume the mean energy of one oscillator equal to $\frac{1}{2}kT$ one third of the thermal energy of the gas particles. Suppose that the oscillation lasts for 0.1 s, and that the average optical depth where the radiation is emitted is equal to τ ; there are N oscillators. The fraction of the energy radiated by an oscillator per unit of time is γ . If the oscillators do not oscillate coherently the total amount of radiation emitted by one oscillator into space is

$$(7.1) \quad e = 0.1 \frac{N}{2} \frac{1}{2} kT \gamma \exp[-\tau].$$

If the electrons would oscillate all coherently (which does not seem *a priori* improbable) we would have in the place of N a factor N^2 in the expression (7.1) (cf. TORALDO DI FRANCA [2]).

Insert

$$\begin{aligned} f &= 200 \text{ MHz, hence } \gamma = 10^{-5}, \\ T &= 2 \cdot 10^6 \text{ }^\circ\text{K}, \\ e^{-\tau} &= 0.1. \end{aligned}$$

Hence the emission of one oscillator is

$$(7.2) \quad e = 5 \cdot 10^{-8} \cdot \frac{1}{2} N kT = 7 \cdot 10^{-18} N \text{ erg}.$$

We next take a strong burst, with an average intensity of $3 \cdot 10^{-21}$ MKS, in average bandwidth $\Delta f = 4$ MHz and a duration of 0.5 s. The integrated flux density at the earth is then $6 \cdot 10^{-8}$ erg m⁻². Assuming that the emission takes place on a solid angle of π steradians, then the total energy radiated into outer space would be $4.25 \cdot 10^{15}$ erg.

Comparing this result with the quantity (7.2) we see that we need about $6 \cdot 10^{32}$ oscillators to emit the observed radiation. If all the electrons would oscillate coherently we would even need only $2 \cdot 10^{16}$ electrons.

On the other hand the volume over which the emission takes place must be rather small notwithstanding the large observed areas of the bursts. If a burst is excited in 0.1 s by an exciting mechanism travelling at a speed of 10^3 to 10^5 km/s, then the diameter of the emitting region must be between 100 and 10^4 km.

We can also find that the true burst area must be small by considering the influence of scattering on the angular extent of the sources: with expression (2.9) applied to the case of the selfemitting layer, assuming, that the bursts are emitted at $0.4 R_{\odot}$ above the solar surface (FOKKER, this volume, p. 385); that at that level $(\Delta N_e)^2/l = 2 \cdot 10^4$ (SCHEFFLER, see reference in Chapter II), and that the path of integration is $5 \cdot 10^{10}$ cm, we find that a burst of zero angular diameter should be observed as one with a diameter of $3'$, which is of the same order as the observed areas.

These two results do not contradict, so that we may assume that the true burst areas can be rather small. Above we found that one strong burst should be emitted by $6 \cdot 10^{32}$ oscillators. At $\varrho = 1.4$ the electron density in an activity centre is about 10^8 cm^{-3} . So if all electrons of a given volume would oscillate simultaneously we would need a volume of $6 \cdot 10^{24} \text{ cm}^3$, having a radius of $1.8 \cdot 10^8 \text{ cm} = 1800 \text{ km}$.

So, what we need is one big volume of oscillating electrons, where the total number of oscillating electrons is so great that the radiation of the bursts is not emitted by a small number of isolated oscillators but rather by large scale *plasma oscillations*.

The next problem is whether perhaps plasma oscillations could be much more efficient in emitting radiation than single oscillators.

In the following sections we will shortly examine the radiation properties of plasma oscillations. It will prove that there are two fundamental difficulties; they will be shown in Sections 2 and 3.

2. - No radiation from a homogeneous oscillating plasma.

An oscillating plasma appears to not radiate at all (apart from the contributions of all individual oscillating and radiating particles) because in the plasma oscillations the real current is continuously compensated by the displacement current. This can be shown as follows (I owe this derivation to Dr. FOKKER).

We consider only motions of electrons; the ions are supposed not to oscillate. Oscillations occur in the X direction.

- Let: N be the mean electron density;
 n the deviation with respect to the mean value;
 v the average velocity.

The equation of continuity can be written as

$$(7.2) \quad \frac{\partial n}{\partial t} = -N \frac{dv}{dx} \quad \text{or} \quad i\omega n = ikNv.$$

Poisson's equations is

$$(7.3) \quad \frac{\partial E}{\partial x} = -4\pi ne \quad \text{or} \quad ikE = -4\pi ne.$$

The current is $j = -N_e v$; (7.2) and (7.3) yield

$$(7.4) \quad Nev = \frac{\omega ne}{k} = \frac{i\omega E}{4\pi} = \frac{1}{4\pi} \frac{\partial E}{\partial t}.$$

Hence

$$-j = \frac{1}{4\pi} \frac{\partial E}{\partial t} \quad \text{or} \quad 4\pi j + \frac{\partial E}{\partial t} = 0.$$

So we find, with Maxwell's equation,

$$\text{rot } \mathbf{H} = \frac{1}{c} \left(4\pi j + \frac{\partial \mathbf{E}}{\partial t} \right) = 0.$$

Because of the compensation of the real current by the displacement current the oscillating electric field of a plasma is not related to a variable magnetic field. Hence the Poynting vector of the emitted radiation $\mathbf{S} = c/4\pi[\mathbf{E} \wedge \mathbf{H}]$ is zero. So apart from the contributions of the individual oscillating electrons no increase of the radiation field of a plasma is to be expected. A great many investigations have been devoted to the problem whether under certain circumstances an oscillating plasma perhaps still does emit radiation. However, even if we could manage to find a radiation mechanism we are still left with the difficulty that at the sharp plasma frequency, radiation, if emitted by some mechanism, can not propagate. So we certainly need a widening mechanism. We will start with the discussion of the second problem.

3. - The dispersion relation for a plasma.

With the same assumptions as those used in Section 2 we will determine the dispersion relation: the relation between the frequency of oscillation of the plasma ω , and the wavelength of the emitted radiation $\lambda = 2\pi/k$.

Besides the assumptions of Section 2 we assume the electric field parallel

to the X -axis. The varying quantities n , E and V are proportional to $\exp[i\omega t - ikx]$. The thermal velocity of the individual electrons in the X direction is u .

In the equation of momentum transfer

$$(7.5) \quad Nm \frac{dv}{dt} + \text{grad}(Nmu^2) + N_e E = 0,$$

we can neglect products of small quantities so that (7.5) becomes

$$(7.6) \quad N \frac{dv}{dt} + 3\bar{u}^2 \frac{\partial n}{\partial x} + \frac{N_e}{m} E = 0.$$

The factor 3 in the second term comes from the fact that the electron density variations are adiabatic $u^2 \sim N^{\gamma-1} = N^2$, ($\gamma = 3$). We differentiate (7.6) to x , use (7.2) and (7.3), and get the dispersion relation:

$$(7.7) \quad \omega^2 = \omega_p^2 + 3\bar{u}^2 k^2.$$

Here $\omega_p = 4\pi N_e^2/m$.

We see that the plot of k^2 against $(\omega^2 - \omega_p^2)$ yields zero for $\omega = \omega_p$. For that frequency of oscillation the associated electromagnetic wave will not propagate. In order to obtain an idea of the quantities involved in (7.7) we could take $T = 10^6$ °K, making $u \approx 6\,000$ km/s and $3\bar{u}^2 = 10^{18}$.

For $\lambda = 150$ cm, $\omega_p^2 = 1.6 \cdot 10^{18}$.

4. — Radiation by plasma oscillations.

After these introductory considerations on the character of plasma oscillations we rapidly consider the various suggestions, found in literature to increase the emission of an oscillating plasma above the contribution of the sum of the individual radiating oscillating electrons.

a) Magnetic fields. We know that an oscillating collective does not emit radiation because no variable magnetic component is produced: $\text{curl } H = 0$. So a first suggestion is whether a plasma oscillating in a magnetic field might loose its longitudinal character; by induction a magnetic component might originate, thus yielding a non-zero Poynting vector. We know that the Appleton-Hartree formula shows that in a magnetic field region $n \neq 0$ around the plasma frequency. This case was discussed by LÜST [3], who indeed found that a non-zero Poynting vector could result from such oscillations. It seems to us, however, that this Poynting vector is extremely small, thus yielding

an amount of radiation, negligibly small as compared with the own radiation of the electrons.

b) « *Turbulence* ». LARENZ [4] considered the case of an oscillating plasma moving as a whole into a direction, making an angle $\vartheta (\neq 0)$ with the direction of propagation of the plasma oscillations. We simplify the problem by considering $\vartheta = 90^\circ$, hence the plasma moves in the sightline direction. The successive space charges represent an alternating current for an observer situated in the z -direction (Fig. 19). This current has only a z component $j_z = v$. This leads to a transverse oscillating magnetic field H_y , perpendicular to the plasma oscillations and to the plasma drift. This alternating magnetic field produces a coupled alternative electric field into the z direction and thus electromagnetic radiation can be generated in this plasma. Since the magnetic field and the divergence-free component of the electric field are perpendicular to the direction of motion of the space charge waves the resulting Poynting vector of the electromagnetic radiation is parallel to the direction of the density waves.

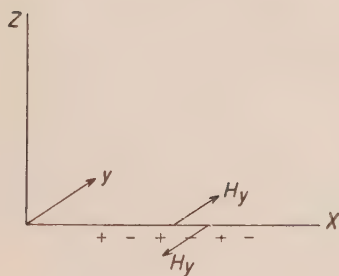


Fig. 19.

Since the magnetic field and the divergence-free component of the electric field are perpendicular to the direction of motion of the space charge waves the resulting Poynting vector of the electromagnetic radiation is parallel to the direction of the density waves.

FOKKER [1] has criticized this theory stating that Larenz's computations are equivalent to a transformation of the system to that of a plasma at rest and a moving observer. This should mean that the plasma would only radiate e.m. radiation if the observer moves. This criticism is correct but it does not apply to a next version of Larenz's theory [5] in which he has considered plasma oscillations in a field of turbulent motions. Since turbulence has a curl it can not be transformed away. So it seems that Larentz's results can be applied to the solar corona. An estimate of the radiation emitted by this mechanism leads to acceptable values for the radiation current.

Nevertheless it remains questionable whether turbulence of the kind considered by LARENZ does actually occur in the corona.

c) *Inhomogeneities*. Some investigators suggested the so-called antenna theories. Just as in an antenna the oscillating electrons might produce radiation. However, in an homogeneous medium this will not be the case; the phases of the different waves will cancel each other. But if the medium is inhomogeneous an electromagnetic wave of sufficient energy might be emitted as soon as the amplitude of the plasma wave changes considerably over a distance of the order of the wavelength of the longitudinal waves (SEN [6]).

The treatment of Sen has been subjected to criticism by ZHELEZNIKOV [7], who refined the mathematical treatment and discussed the coronal inhomogeneities. Coronal inhomogeneities with a wavelength of $6 \cdot 10^4$ cm were as-

sumed, and it was found that oscillation energy can be transformed into radiation energy with an efficiency factor of $3 \cdot 10^{-7}$. This efficiency is only of the same order as the efficiency with which the normal electromagnetic radiation from the oscillating electrons is emitted. Furthermore it seems questionable whether such inhomogeneities can exist.

Summarizing, it seems to us that the actual theory of radioemission by a plasma as a collective phenomenon does not seem to give an appreciable increase of the emitted radiation above the contribution of the sum of the individual oscillating electrons. Since the latter mechanism seems already capable of explaining at least some properties of radiobursts, we are inclined to keep for the time being to the way of approach exposed by us in Chapter VI.

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INTERVENTI E DISCUSSIONI

DISCUSSION TO DE JAGER'S LECTURE I

— A. D. FOKKER:

Is it perhaps possible to understand the differences between the low and the high temperatures of the corona ($8 \cdot 10^5$ °K and $15 \cdot 10^5$ °K) by assuming thermal inhomogeneities.

— C. DE JAGER:

Yes this was done by Shklovski on the basis of his computations of the ionization equilibrium. With Elwert's new ionization computations for the corona it looks more difficult to explain the observations on the basis of inhomogeneities.

- A. D. FOKKER:

Also for the explanation of scattering, inhomogeneities are necessary.

— C. DE JAGER:

Yes.

— G. ELSTE:

In Piddington's method to find the temperature distribution in the transition region chromosphere-corona a discontinuity is introduced purely mathematically because of the quadratic term. With another mathematical expression we would get rid of the δ function.

— C. DE JAGER:

Yes.

— G. ELSTE:

Might the rise of temperature at 4 mm be due to another solar absorption coefficient.

— C. DE JAGER:

No such absorbing mechanism is known.

— J. P. WILD:

At long wavelengths the sun is no longer a black body, it is gray; because of the refraction of the rays the total optical path computed along one ray may be small.

— C. DE JAGER:

(Answer is contained in the printed first lecture; the effect is only important for $\lambda \geq 10$ m).

— K. O. KIEPENHEUER:

Inhomogeneities are also to be expected at the basis of the cooling mechanism presented by me yesterday. If a part of the corona becomes dense it cools and becomes more dense.

DISCUSSION TO DE JAGER'S LECTURE V

— R. STEINITZ:

In describing the shielding length λ_s of the magnetic field it was assumed that $H_{\text{initial}} \approx H_{\text{induced}}$. This contradicts energy conservation, as the particles accelerated by the initial field, while inducing an opposite field also reduce the initial field. Therefore λ_s calculated by this method does not represent the true characteristic dimensions.

— C. DE JAGER:

Yes, λ_s could be incorrect by a factor 10 or so but at the present state of theory it is needless to go into more detail.

— K. O. KIEPENHEUER:

Your computation of λ_s is erroneous; I derived an expression for the shielding distance some days ago: $l = (1/c)\sqrt{\sigma/\tau}$. The acceleration distance may be of the order of 10^9 cm in a direction perpendicular to the shielding distance vector, then producing particles of some MeV.

— C. DE JAGER:

I am afraid you confuse the depth of penetration of the magnetic field into an approaching cloud of gas moving perpendicular to the field, and the distance over which magnetic induction effects are important. They are different things.

— K. O. KIEPENHEUER:

Your way of accelerating particles over the shielding distance does not seem correct. I would prefer the mechanism I exposed in my lectures. Furthermore, you applied the theory of a *flare* to compute the *accelerations*.

— C. DE JAGER:

This acceleration theory has formerly erroneously been applied to flares when people were thinking that flares are hot and that great accelerations were needed to heat a flare. However I strongly believe that the main phenomenon of a flare is the compression and the subsequent cooling (so that in order to get a flare, it is rather a deceleration of the thermal velocities that we want). As a next effect we want an acceleration, and for it the older flare mechanism seems well suited.

— K. O. KIEPENHEUER:

I am inclined to believe that the acceleration of type II matter is (as GIOVANELLI showed) identical with a surge. The surge is the effect of the electric currents in the flare on the coronal matter.

— C. DE JAGER:

Surges have an average velocity of $(50 \div 100)$ km/s. You should then introduce invisible, high velocity surges.

— K. O. KIEPENHEUER:

You said that the observations of the weak expansion of prominences during their ascent proves that they are kept together, presumably by a field, brought upwards with the prominence. But it is only a consequence of lack of diffusion. The diffusion velocity of the field with respect to the matter is small.

— C. DE JAGER:

In any case this is another way of saying that the field is brought upwards with the prominence.

— R. STEINITZ (to KIEPENHEUER):

The shielding distance considered by you is a different thing than the one considered by DE JAGER.

— K. O. KIEPENHEUER:

The equations are different but it is the same thing.

— R. STEINITZ (to DE JAGER):

Has anybody considered the diffusion of prominence matter into the corona.

— C. DE JAGER:

It depends on the sort of diffusion. In a magnetic field it goes slowly. If we take no magnetic field then the viscosity of the corona would permit velocities of fall of 30 km/s.

— M. MINNAERT:

The forces acting in a prominence may be different from one point to another; it will have influence on the speed with which the shape of the prominence changes.

— K. O. KIEPENHEUER:

The prominence is lifted with the corona.

— M. MINNAERT:

If type III bursts are due to accelerated electrons, are you not afraid for electric attraction of the electrons by the positive ions.

— C. DE JAGER:

For very fast electrons the interaction with the surrounding protons is extremely small, so that will give no difficulty. But finally, when the cloud is to leave the corona electrostatic attraction becomes important and I believe this may lead to the type V bursts.

— J. P. WILD:

A cloud of accelerated electrons will rapidly expand.

— M. MINNAERT:

It would be useful to consider the electrostatic repulsion quantitatively.

— C. DE JAGER:

The collisional cross-section is small for high velocity particles; this increases the probability of an electron jet.

— K. O. KIEPENHEUER:

An electric jet through the corona is absolutely impossible. We need a theory explaining type III bursts as neutral jets.

— M. MINNAERT:

Do these electrostatic repulsion forces apply to the corona? There will be furthermore electrodynamic attraction.

— K. O. KIEPENHEUER:

The repulsion force is the most important one.

— J. P. WILD:

The size of a type III cloud expands rapidly as it goes up, but this may be due to scattering.

DISCUSSION TO DE JAGER'S LECTURES VI AND VII

— G. TORALDO DI FRANCIA:

In plasma oscillations the current will not be compensated exactly by the displacement if the volume considered is finite.

— C. DE JAGER:

Yes, in a sense this is the problem of the inhomogeneities.

— J. P. WILD:

I can't see a real difficulty in the problem of propagation. A pulse sent to the sun and being reflected by the very plasma level comes back in a finite time although the velocity of propagation is zero, for an infinitely short time.

— C. DE JAGER:

Yes, a very small widening of the line will be sufficient for a great part of the radiation to escape.

— J. P. WILD:

GALLET seems to have worked out a theory showing that an appreciable space charge can be obtained if a shock wave moves so that the velocity distribution contains two definite maxima. This occurs for about $3 \times$ sound velocity, *i.e.* 500 km/s, which agrees with the lower cut-off for the type II velocities. I wonder whether Larentz's computations may also explain the lower cut-off for type III velocities (observed at round 60 000 km/s) by the condition that the electron stream (presumed to be the exciting agency) must be substantially greater than the mean velocity of thermal electrons ($\approx 6 \cdot 10^3$ km/s).

— C. DE JAGER:

The greater the speed the greater the space charge separation. The problem should be worked out quantitatively. The lower cut-off of the velocity spectrum of type III bursts could be explained assuming again that these bursts are due to *electron* jets: for speeds of that order the mean free path of the electrons is greater than the scale height of the corona. This is another argument for explaining type III bursts as being excited by electron jets.

— K. O. KIEPENHEUER:

Do the electrons emitting a burst oscillate coherently?

— C. DE JAGER:

In the preceding discussion I assumed them to oscillate incoherently. It is, however far from certain that this is really true.

COLLOQUI

Colloquium on the Effects of the Solar Activity on the Cosmic Ray Intensity at the Earth.

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1. - Introduction.

A short account is given of the main effects of the solar activity on the Cosmic Ray (C.R.) intensity at the Earth, which are listed below according to an increasing time scale of the effects.

- a)* Sudden increases associated with solar flares (duration: 2 to ~ 15 hours);
- b)* Forbush-type decreases (duration: 2 to 20 days);
- c)* 27-day recurrence tendency.
- d)* 11-year variation.

Some experimental data on the general features of these variations are reported with particular reference to the results obtained in Rome since 1954 and to a few results reported at the recent Moscow C.R. Conference (July 1959). Particular emphasis is given to the effects *b)* and *d)* which are usually interpreted as due to a shielding effect of solar corpuscular streams on the galactic C.R. intensity. The effect *c)* is only mentioned as an effect of small amplitude (a few %) analogous to the 27-day recurrence in the geomagnetic activity, to be referred to the synodic period of the solar rotation. Its character however has not yet been settled.

As a background in the description of these variations some general properties of the Cosmic Radiation are reminded, as: galactic origin; isotropy of the primary Cosmic Radiation outside the geomagnetic field and outside the atmosphere; charge spectrum and energy spectrum of the primary Cosmic

Radiation; geomagnetic latitude effect; development of the Cosmic Radiation through the atmosphere, producing the different secondary components recorded at ground stations, mainly the meson component recorded by G.M. counter telescopes and the nucleonic component recorded by neutron monitors.

A complete review on the primary Cosmic Radiation and its variations can be found in reference [1].

2. - Sudden increases associated with solar flares.

On five occasions since the C.R. intensity has been continuously recorded (*i.e.* from 1937 to the present time), sudden increases in the intensity at ground stations have been observed, following large solar flares at a very short time distance after the optical observation (in the event of 23 February 1956 the delay was in some stations as small as 8 minutes). The time and amplitude parameters of these events for different recording stations have been studied carefully; this analysis has brought to the conclusion that on these occasions low energy cosmic rays have been emitted from the sun. The effect is well known to the solar physicists (see for instance the review on the subject in reference [2]) and possible mechanisms of the C.R. emission from the Sun have been already discussed here in Varenna.

Recent balloon, rocket and satellite measurements [3-5] show that on many more occasions solar cosmic rays reach the vicinity of the earth or the upper atmosphere, although no increase is recorded at the same time at ground stations. These events, corresponding obviously to lower-energy solar cosmic rays than the previous ones, have to be studied as a complementary information about solar emission of cosmic radiation.

3. - Forbush-type decreases.

A less spectacular but more frequent effect of the solar activity is given by the Forbush-type decreases or C.R. storms. These are steep decreases (up to $(10 \div 15)\%$ decline in 2 hours in some cases in the neutron component at sea level) followed by a slow recovery to the pre-storm level, in a time interval which can range from 2 to 20 days (see for instance Fig. 1).

The frequency of occurrence of such events (23 in 13 months during the solar maximum 1957-58; much lower frequency during the solar minimum), the correlation with geomagnetic storms and, at a time delay of the order of one day, with solar flares make the subject of the highest interest in the study of the geophysical effects of the solar activity.

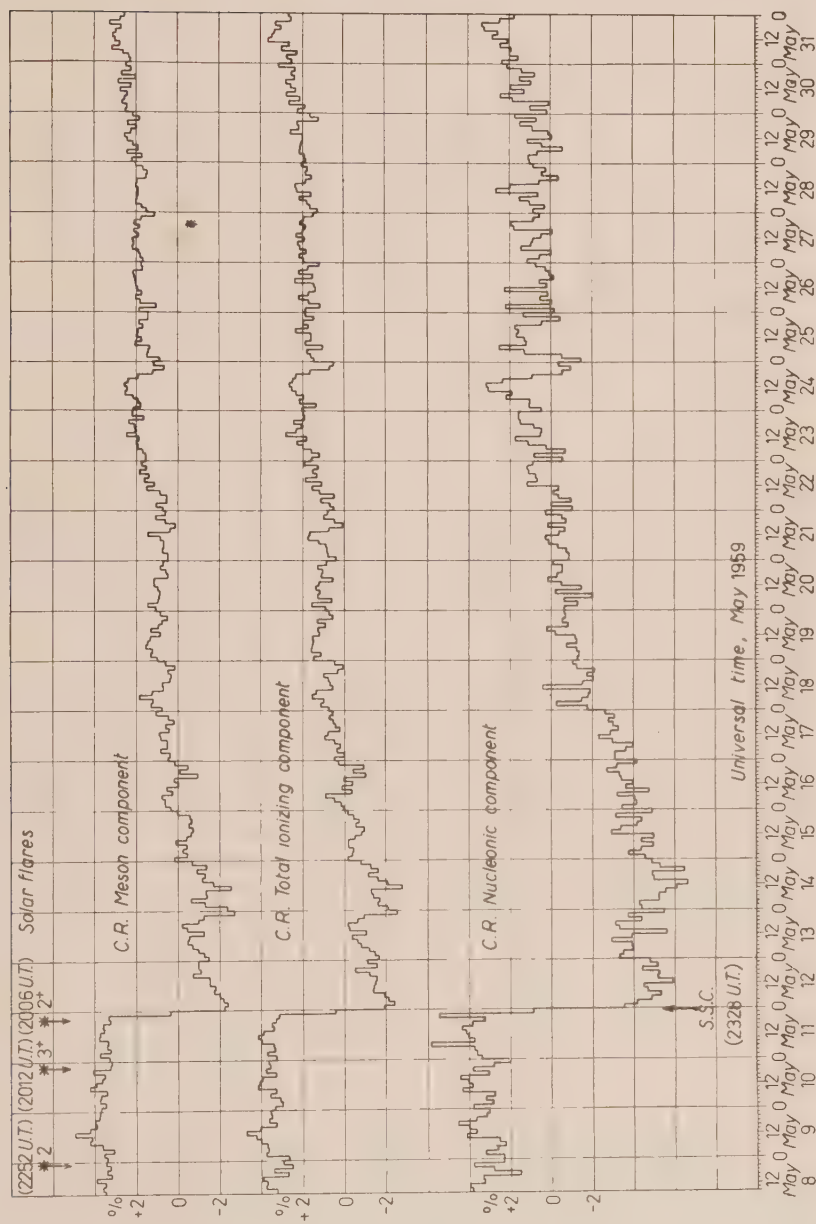


Fig. 1. The C.R. storm of May 11, 1959, as recorded at the SVIR(+) station, Rome (F. BACHELET, P. BALATA, A. M. CONFORTO, N. IUCCI and G. MARINI: *Nuovo Cimento* **13**, 1055 (1959)).

3.1. *Correlation with geomagnetic storms.*

a) Results obtained at SVIRCO Station in Rome [6] (nucleonic component; selection of the events by means of 5 world-wide station-recording). 24 C.R. events (Forbush-decreases) were classified, occurred from July 1957 to July 1958. Out of them, 20 were found to be in coincidence with Sudden Commencement Geomagnetic Storms, taking into account both storms with initial phase and main phase and storms with initial phase only, while 1 event was in coincidence with a Gradual Commencement Geomagnetic Storm. For these 21 events the starting times of the C.R. decrease and of the associated magnetic storm agree within the accuracy of the C.R. event, which ranges from $\frac{1}{2}$ to a few hours. Only 3 C.R. events are not associated with magnetic events. The total number of «typical» geomagnetic storms in the same period is 58, so that only 35% of them is associated with C.R. events. There is no similarity in the variation of the geomagnetic field and of the C.R. intensity, so that the former variation cannot be the cause of the latter; a common cause acting in two different ways should be looked for.

b) Results obtained in Bologna [7]. The maximum in the variability index of C.R. intensity occurs on average 12 hours earlier than the maximum of K_p indices of geomagnetic activity. The asymptotic directions of particles entering a given telescope at a given station are derived so that anisotropies in the C.R. events are studied.

c) Interpretation. A general picture of the loosely associated geomagnetic and C.R. phenomena can be the following [8-10]. Solar corpuscular streams of plasma reach the earth and produce geomagnetic storms because of their high conductivity. They can also carry out with them «frozen-in» magnetic fields, which deflect C.R. particles away from the earth causing an intensity decrease with an energy-dependent amplitude (latitude and altitude effect on the amplitude at different stations). One unsettled problem is whether the «frozen-in» fields are ordered or disordered: there is some support to the statement that the Astronomical Unit is a right distance for a stream to become disordered. The preferred correlation of C.R. events with Sudden Commencement Geomagnetic Storms (see point *a*)) should be an indication for the parameters of the solar clouds, required to trigger both the geomagnetic and C.R. perturbation.

3.2. *Correlation with solar activity.* – Very interesting preliminary results were reached by Y. KAMIYA and M. WADA (Japan) [11].

A total of 25 C.R. decreases occurred during the 18 months of the IGY 1957-58 were studied. A correlation 1 to 1 was found with large solar flares (importance ≥ 2) accompanied by a Type IV radio burst, except when

the solar event occurs during the recovery time of a previous Forbush-decrease. The C.R. event follows the solar flare and burst at a time delay of the order of one day in agreement with the time delay found for the magnetic storms. From the longitude distribution on the solar disk of the flares associated with C.R. events and of those associated with geomagnetic events some consequences are inferred for the parameters of solar corpuscular streams or clouds (narrow angle, high density core emitted radially for the magnetic storms; wide angle, high magnetization beam for the C.R. decreases). No details are given about the selection of both C.R. events and of solar radio bursts, so that the significance of the inferred correlation 1 to 1 cannot be examined at the moment. Nevertheless these results supply one more evidence of the role of the Type IV radio bursts in these solar events which are responsible, through the emission of plasma clouds, of so many geophysical effects.

4. - Eleven year cycle.

The monthly means of C.R. intensity show a negative correlation with the monthly Sunspot Number as well as with other indices of solar activity. This effect has been investigated already for 2 solar cycles by FORBUSH [12] (measurements from 1937 to 1958).

Results of measurements of the total component in Rome from 1954 to 1957 [13] are presented along with analogous results obtained in Japan and in Canada in the same period. Different profiles of the C.R. intensity versus time at different stations show a latitude and altitude dependence, *i.e.* an energy-dependence of the effect of solar activity on cosmic rays. Complementary upper atmosphere measurements show that both the number and the energy spectrum of the primary C.R. particles undergo changes during the solar cycle. Again a shielding effect by solar corpuscular streams is usually invoked, which is increasing with increasing solar activity: so that only at the time of the solar minimum, if at all, the true galactic flux of cosmic rays is seen at the earth.

5. - The Van Allen radiation belts.

Some recent information [14] is reported about the two radiation zones surrounding the earth.

For the inner zone (altitude about $\frac{1}{2}$ Earth's radius a.s.l.; electrons with energy up to about 1 MeV; protons with energy of the order of 100 MeV) the composition and the energy spectrum of the radiation is not inconsistent with the hypothesis of an albedo effect on cosmic rays by the terrestrial

atmosphere, the decay products of the emerging particles being trapped in the geomagnetic field.

For the outer zone (altitude about 3 Earth's radii a.s.l.; only electrons up to $E = 100$ keV) the radiation is interpreted as a part of solar corpuscular streams captured by the geomagnetic field and locally accelerated perhaps by means of hydromagnetic waves.

The time variations show a great influence of the solar activity on the intensity and extension of the outer zone, so that the possible role of this radiation belt in the geophysical effects as a reservoir of solar particles is emphasized.

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INTERVENTI E DISCUSSIONI

— C. DE JAGER:

There is an explanation for the scattering zone at $R > 1$ Astr. Unit, to which you referred. At a colloquium in Jena, some years ago (to be published in *Sterne*) I presented a theory in which I could estimate that collisions between the numerous fragments of small planetoids in the planetoid zone will produce an ionized, turbulent gas. By transforming the kinetic energy of turbulence into magnetic energy, fields of the right order of magnitude (10^{-5} G) could be explained.

Fast-Response, Narrow-Band Spectroscopy.

T. DE GROOT

Radio Observatory - Dwingeloo

The broad-band dynamic radio spectroscopes, now in use in various parts of the world, yield in an effective way a large amount of information about transients in solar radio noise. The results have fundamental value for any further research. The spectrograms give a survey of what has happened within a large frequency range, and we can classify the events in an unambiguous way, sometimes finding new varieties. The classification concerns mainly the «macro-structures», which by definition may be all those, which can be resolved by the instrument, that is: with characteristic times > 5 seconds, say.

It has long been known, that the characteristic times in *e.g.* noise storms are much less (0.1 s), and one can ask quite generally, if «micro-structures» have features, which are characteristic for the large scale event they belong to. Moreover they may make possible further classification of noise storms. Apart from these considerations, micro-structures as such may be related more directly to the conditions in the plasma, or to a hypothetical enigmatic agency which generates them.

To study these stormbursts (or more generally pips), we use an eight-channel receiver (designed mainly by J. T. DE JAGER), with which they can be recorded simultaneously at eight adjacent frequencies. The total bandwidth is 14 MHz, the channel-bandwidth 1 MHz. The difference of the right-handed (R) and the left-handed (L) polarized components at the centre frequency can also be determined. The outputs are fed into an eight pen fast recorder with a response time of 0.01 s, using paper speeds of $(1.5 \div 4)$ cm/s. Full scale is about equivalent to the quiet sun intensity, the noise fluctuations set the lower limit of bursts which can be distinguished with certainty, to about 5% of that intensity.

In this way we get a survey of what is happening within a relatively narrow

frequency band of 14 MHz, and can plot iso-intensity curves in the frequency-time plane. Up to now, the instrument has been working at $(382 \div 396)$ MHz and $(324 \div 336)$ MHz, during a couple of months in each case.

Some results may be summarized as follows:

1) Single isolated stormbursts have an average duration of (0.2 ± 0.03) s at both frequencies (time-interval between half-power points). The profiles seldomly show much asymmetry. (This we knew already from measurements with a single channel receiver, which preceded the present one.)

2) The frequency profiles (intensity versus frequency) have a gaussian shape in about 30% of cases, with an average half power width of (7 ± 2) MHz at both frequencies. The band-width does not change very much during the life-time of a burst.

3) The remaining 70% on the contrary yield very irregular frequency profiles indeed and *may* be regarded as a superposition of «neat» bursts (as sub 2)), jostling each other in the frequency time plane.

4) As to polarization, the «normal» case is, that the sense and—to a lesser degree—the rate of circular polarization does not change during an appreciable fraction of the life-time of a noise storm. The «abnormal» cases are not so very few (about 50%) and most noticeable are those which have no polarization ($P < 3\%$). Linear polarization measurements, occasionally performed, yielded negative results.

5) Frequency drifts can be determined quite accurately ($0.2 f$ per cent, f in MHz/s). In the case of a stormburst, this mean, that the axes of symmetry are not perpendicular to the f —and t —axes. Most stormbursts however are truly type I. Frequently drifts between 50 and 200 MHz/s have been found.

6) «Double» bursts occur rather frequently. Often a burst is double in only one or two channels, showing a dip at the top.

In conclusion, it may be emphasized, that the study of details in solar radio noise in the way described would be most effective, when broad band dynamic spectra were available at the same time.

* * *

The work reported here has been supported financially by the Netherlands Organization for Pure Research (Z.W.O.).

INTERVENTI E DISCUSSIONI

— J.P. WILD:

What exactly do you call stormburst?

— T. DE GROOT:

It is perhaps better to have a neutral name (pips) for all very short-lived transients; I used the name stormburst in that general sense.

— J. P. WILD:

I have a word of warning about possible confusion between type I and type III storms, the latter consisting of weak bursts and lasting some hours, and sometimes overlapping a type I storm.

— M. MINNAERT:

Will the polarization rates be different in these two cases?

— J. P. WILD:

They are very unreliable indicators.

— H.H. RABBEEN:

Comparison with results of the Freiburg spectrograph ($(48 \div 165)$ MHz) could be of some value.

Polarization Behaviour of Enhanced Solar Radio-Emission at 200 MHz.

A. D. FOKKER

Section Ionosphere and Radio Astronomy of Netherlands PTT - The Hague

In this communication I shall tell something about the results of observations of circular polarization at 200 MHz which have been made during the last 4 years at the Nera Observatory (Holland) with a polarimeter built by Mr. F. R. NEUBAUER. This polarimeter has been designed so as to record both the sum and the difference of the right- and left-handed circular components. The block diagram of the polarimeter is represented in Fig. 1. Of course it would also have been possible to measure the right- and left-circular components individually, and this is actually done at Cornell University (Ithaca, New York) and at Tokyo.

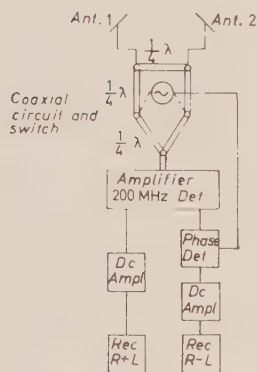


Fig. 1. — Block diagram of the polarimeter.

The differential method, though, is especially advantageous if one wants to detect small degrees of polarization. In fact the Nera polarimeter has proved to yield a very sensitive response to small polarizations. Small traces of polarization sometimes are displayed by isolated outbursts, such as type III outbursts. Such small polarizations moreover may be variable. An interesting example is represented by Fig. 2. On the other hand, many outbursts per-

sistently do not show up even the slightest polarization. One very striking case was observed April 8, 1959. This was on the occasion of a flare-associated outburst of about $4\frac{1}{2}$ min duration, which reached the exceptionally great intensity of over $500\,000 \cdot 10^{-22} \text{ W} \cdot \text{m}^{-2} \text{ Hz}^{-1}$. Yet, the polarimeter showed practically no polarization at all, no more than a few times $10^{-22} \text{ W} \cdot \text{m}^{-2} \text{ Hz}^{-1}$. In this communication I shall restrict myself for the rest to the polarization characteristics of noise storms.

Whenever there are one or more sunspots in the central zone of the solar disk, there is a fair chance that a noise storm will occur. In a noise storm one may distinguish two components: the continuum and the stormbursts. The relative importance of these two components varies greatly for different storms. The continuum and the stormbursts generally originate in approximately the same source region. The sources of storm radiation are intimately connected with certain sunspot regions. As a result of the presence of magnetic fields associated with such a sunspot, the storm emission as a rule is strongly circularly polarized. I shall now proceed to describe into some detail the polarization properties of storms.

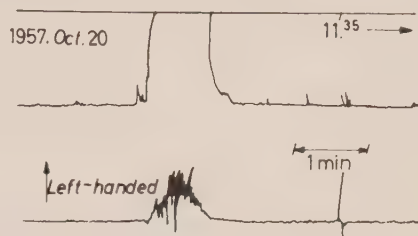


Fig. 2. — Example of small variable polarization during an isolated outburst.

1. — The normal case.

In most well-developed bipolar sunspot-groups there exist two opposite magnetic fields of approximately equal strength, which have their seats in the preceding and in the following parts of the sunspot respectively. Because of this circumstance it would be natural to expect quite a complicated picture of the polarization characteristics of a noise storm, as the source region might well be pervaded both by field lines running upwards and by field lines

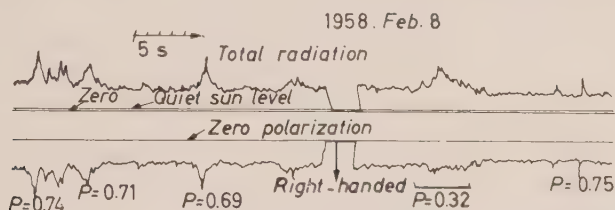


Fig. 3. — Group of bursts during a noise storm with anomalous degree of polarization.

pointing downwards. Nevertheless most noise storms are strongly polarized in one sense only. This appears especially to be the case if one obviously has to deal with one noise-active sunspot region only. Whether this is likely to be the case can be judged from the general sunspot configuration, in combination with interferometric information (for instance there may be only one major sunspot group present which comes into consideration for

being noise-active). So, if one source only produces excess radio noise, both the continuum and the stormbursts are generally strongly polarized in the same sense. This apparently is the normal case, and it seems to indicate that in the region above a bipolar sunspot one of the two opposite magnetic fields predominates. The stormbursts usually have very nearly identical degrees of polarization which are close to 100%. A peculiar thing is the fact, that a few bursts with an anomalous degree of polarization may occur quite unexpectedly during a noise storm which for the rest is very homogeneously polarized (see Fig. 3).

Our observations indicate that the degree of polarization of the stormbursts need not be exactly identical to that of the continuum. In order to evaluate the degree of polarization of the continuum the contribution of the (unpolarized) quiet sun flux value must be taken into account. In adopting a plausible value for this contribution, it is found that the enhanced continuum often is very near to 100% polarized.

2. - Exceptions to the normal case.

Still restricting ourselves to the cases when there is good reason to suppose that no more than one sunspot region contributes to the noise activity, we sometimes encounter anomalous polarization properties of storm radiation. So the following situations have occurred:

- a) continuum strongly polarized, bursts unpolarized;
- b) continuum weakly polarized, bursts strongly polarized;
- c) continuum polarized, bursts have weak but variable polarizations;
- d) continuum and/or bursts weakly or moderately polarized;
- e) variable degree of continuum polarization, right- and left-handed bursts («mixed» polarization from single sunspot region);
- f) identical sense but widely different degrees of burst polarizations.

In those cases where there is a significant difference between the polarization of the continuum and the stormbursts one might think that these two components originate from different parts of a sunspot region. This has been confirmed interferometrically in at least one case. It is only seldom that mixed polarization (case *c*) occurs in the presence of only *one* centre of activity.

3. - Mixed polarization.

Fairly often, when there are two or more important sunspot groups simultaneously present on the solar disk, the presence of both right- and left-handed polarized bursts testifies to the existence of two oppositely polarized

components arising from different sources. In such cases the continuum polarization may fluctuate around zero if the right- and left-handed polarized components alternatively outweigh each other (see Fig. 4). In these cases we may speak of the « superposed mixed » type of polarization. That the bursts of opposite polarization are excited in different parts of the solar disk has been confirmed interferometrically in a few cases.

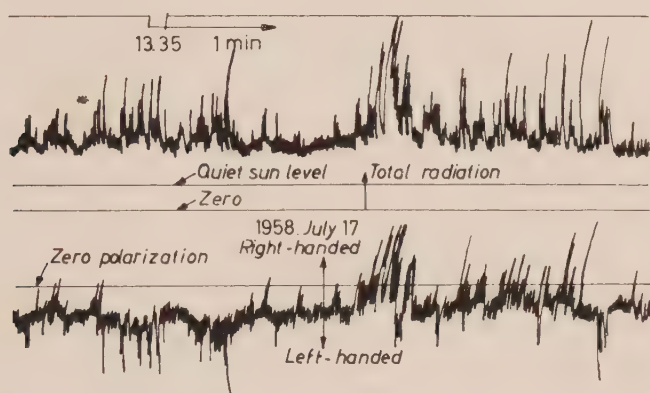


Fig. 4. — Anomalous degree of polarization of a little group of stormbursts.

There is also a type of mixed polarization for which the degree of polarization of the stormbursts is very small and moreover variable. Both right- and left-handed polarizations occur. The small polarizations seem to represent slight deviations from the unpolarized case. There is no reason to assume that the bursts of opposite polarizations originate in separate noise sources. We might speak of an « intrinsically mixed » type of polarization, as the bursts seem to originate in one coherent source region, in the various parts of which apparently slightly different conditions prevail.

4. — Unpolarized storms.

Unpolarized storms are relatively rare, but they do occur. However, storms with a strongly increased continuum flux level almost never are unpolarized. There does not seem to exist a fundamental difference in character between polarized and unpolarized burst activity. This is, for instance, illustrated by the following case. On two successive days the source position was observed to be situated outside the sun's limb, whereas the type of burst activity was very much the same. Still, on the first day the bursts were unpolarized, whereas on the other day they were strongly polarized!

Like the polarized stormbursts, the unpolarized stormbursts have a bandwidth of a few MHz. Great activity of type III-like bursts, though, in some cases bear resemblance to an unpolarized storm.

5. - Progressive development of polarization.

A few cases have been observed of noise storms that initially were unpolarized and which subsequently became strongly polarized. Once when there was spread activity of bursts a rather abrupt change of polarization from unpolarized to polarized was observed. Later on bursts became unpolarized again.

6. - Polarizations of second part flare-associated events.

Several years ago already Mrs. DODSON drew attention to the fact, that flare-associated radio events in a number of cases consist of two parts. The first part, or «early» event, is mostly an outburst of a few minutes duration which starts about simultaneously with the beginning of the flare. These outbursts generally belong to type II or III of the spectral classification.

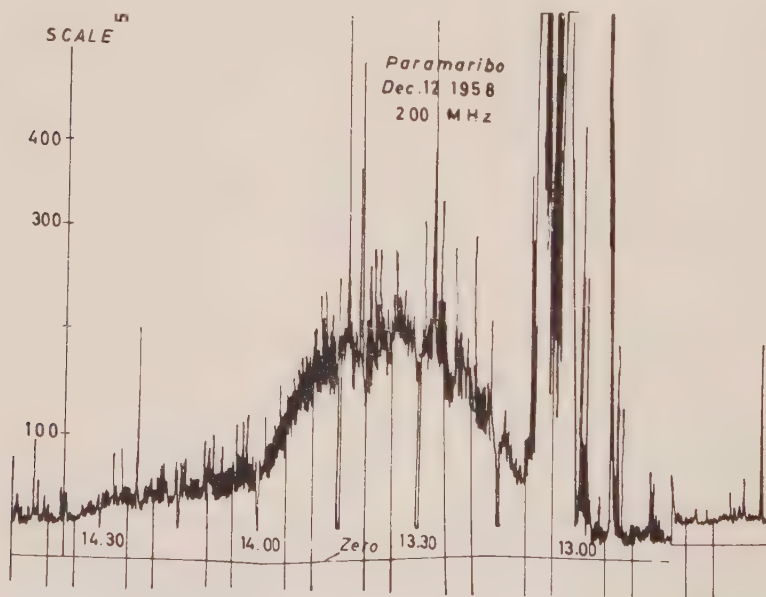


Fig. 5. - Example of the combined occurrence of a first- and second part flare-associated event.

The second part, or « late » event, generally has a longer duration, of $\frac{1}{4}$ hour up to several hours. There may be a delay of several minutes relative to the starting time of the flare, though sometimes the late event starts almost simultaneously with the flare. The second part event may appear as

- a) a very steep rise of intensity followed by a gradual fall;
- b) a relatively smooth rise and fall of intensity (with superposed fluctuations);
- c) complex relatively rapid intensity fluctuations;
- d) an onset of a noise storm.

A fine example of a combination of first- and second part events is given by Fig. 5.

A few years ago a certain category of late flare-associated events was given the name of type IV events. One of the reasons to introduce a new type was the fact that certain of the second part events lacked any variability and thus contrasted with the noise storms. It turned out that these relatively steady enhancements of flux level have a continuous spectrum extending towards the decimeter-wavelengths and presenting a low-frequency cut-off somewhere in the meter-wavelength region. It was suggested by DENISSE, that the mechanism of radiation of the type IV outbursts might be the synchrotron type of emission. For this reason it is particularly worth-while to study the polarization properties of these events. Now, the situation in this respect is somewhat disappointing, in that the polarization behaviour of second part flare-associated events does not obey a fixed rule. This might indicate that these outbursts do not represent a homogeneous category. As a matter of fact, many different intensity profiles are displayed by the various events (see the above subdivision). The situation as concerns polarization is as follows:

- a) Some of the events are strongly polarized from their very beginning.
- b) Others show progressive development of polarization. They may start by being unpolarized, weakly polarized or irregularly polarized. After some time ($\sim \frac{1}{4}$ hour) they become strongly polarized into one sense and remain to be so. Whenever there is progressive development it always is towards strong unidirectional polarization.
- c) Finally, certain events are unpolarized. Maybe such outbursts in some cases should rather be considered as first part, or early, events, notwithstanding their long duration.

Progressive development of polarization during flare-associated outbursts might be connected with changes in the magnetic field configuration as a consequence of the eruptive processes associated with the flare. In this connection

I recall the phenomenon of the activation of filaments which, as Professor MINNAERT said, also might be related to changes of the magnetic field.

7. — Polarization and sunspots.

I want to return once more to noise storms in saying a few words on the relation between sense of polarization of noise storms and sunspots.

In order to have the possibility of quickly surveying the association of radio sources to sunspots and the main polarization behaviour of these sources, I have prepared a sunspot catalogue which covers the International Geophysical Year. A fragment of it is represented in Table I. Only major sunspots have been entered and they are designated by their Brunner types. Horizontal dashes denote whether on a particular day a given sunspot was moderately (single dash) or strongly noise-active (double dash), vertical dashes indicate whether the emission was right- or left-handed polarized. Such dashes, if placed above a horizontal dash, refer especially to the polarization of part or all of the stormbursts whenever this polarization was opposite to that of the continuum (for example in the case of mixed polarization). Whenever more than one sunspot may have contributed to the noise-activity, all these spots are provided with the pertinent symbols, but they are put between parentheses. A + mark above the sunspot symbol indicates a high level of flare activity.

On inspecting this catalogue one arrives at two main conclusions:

1) The sense of polarization of the noise emitted by a particular source region almost without exception remains constant throughout the period of « visibility » of the source.

2) In the present sunspot cycle sources on the northern hemisphere emit predominantly left-handed polarized radiation and vice-versa.

On assuming that the sense of polarization is determined by the magnetic field of the preceding sunspot, the hemisphere relation implies that the observed radiation corresponds with the ordinary magneto-ionic component. However, the opposite behaviour, *viz.* that a northern source emits right-handed polarized radiation, or vice-versa, is no exception. For instance, on a number of occasions when two noise-active sunspot regions were situated on the same hemisphere, mixed polarization has been observed.

Of special interest is the (rare) occurrence of *mixed* polarization in radiation coming from *one* activity centre. Only *one* sense of rotation may be expected normally to emerge, *viz.* the sense belonging to the ordinary mode. It corresponds with that particular magnetic field which the ray witnesses when

TABLE I. - Fragment of a sunspot catalogue.

1957	East						CMP	West					
	-6	-5	-4	-3	-2	-1		+1	+2	+3	+4	+5	+6
Nov. 23 -11°					Nov. 21 A	22 C	23 D	24 (D)	25 (=E=")	G26	27 G	28 G	29 J
Nov. 25 -13°	Nov. 19 H	20 G	21 G	22 E	23 E	24 =G="	25 (=G=")	26 H	27 H	28 H	29 H	30 H	Dec. 1 J
Nov. 26 -15°					Nov. 24 (G)	25 (G)	26 -E"	27 -E"	28 E	29 G*	30 G	Dec. 1 G	2 H
Nov. 29 -19°			Nov. 25 A	26 C	27 C	28 E	29 -E"	30 -E"	Dec. 1 -E"	2 -E"	3 -E"	4 E	5 G
Dec. 3 -18°	Nov. 27 E	28 E	29 E	30 E	Dec. 1 E	2 E	3 -E"	4 -E"	5 -E"	6 -E"	7 E	8 E	9 E
Dec. 11 +11°				Dec. 8 A	9 A	10 B	11 D	12 E	13 E	14 D	15 D	16 D	17 J
Dec. 19 -16°	Dec. 13 E	14 E	15 E	16 E	17 E	18 E	19 (E)	20 (G)	21 (G)	22 (G)	23 G	24 G	25
Dec. 20 +17°	Dec. 14 E	15 -E"	16 (-E-")	17 -E"	18 =F="	19 =F="	20 =F="	21 =F="	22 (=E=")	23 (=E=")	24 E	25 E	26 H
Dec. 21 +23°	Dec. 15	16 (-E-")	17 (-E-")	18 (JH)	19 (JH)	20 (JH)	21 (JH)	22 JJ	23 JJ	24 J	25 J	26 J	27 J
Dec. 22 +15°	Dec. 16 H	17 (-H-")	18 (D)	19 (D)	20 (E)	21 (E)	22 (=E=")	23 (=E=")	24 E	25 E	26 (-E-")	27 D	28 J
Dec. 23 -25°	Dec. 17 A	18 (D)	19 (E)	20 (E)	21 (E)	22 (=F=")	23 (=F=")	24 F	25 F	26 (-F-")	27 H	28 H	29 H
Dec. 24 +23°	Dec. 18 H	19 H	20 E	21 E	22 (E)	23 (E)	24 F	25 F	26 (-F-")	27 F	28 (-F-")	29 F	30 F

Horizontal dashes indicate that a spot has been noise-active (single; moderately; double; strongly). Vertical dashes denote the sense of polarization. Sunspots that could not be identified unambiguously as noise-active put within parentheses. A + mark above the sunspot symbol indicates a high level of flare activity.

The other possibility is to attribute the polarization to the different propagation conditions for the two magneto-ionic modes. For the escape of ordinary radiation the conditions are much more favourable than for the escape of extraordinary radiation. It is plausible that above a center of activity there is an extended region from which only the ordinary magneto-ionic component can escape. This is illustrated by Fig. 6, which shows a schematic model chosen in such a way that radiation of essentially one sense of polarization would be emitted into outer space.

In this paper I dealt only with circular polarization. This is the state of polarization which one would naturally expect and which normally is observed. It is possible, though, to measure, more generally, elliptical polarization. Attempts to make such measurements, which in principle are relatively simple, but in reality prove to be difficult, have been undertaken at the Tokyo, Cornell and Nera observatories. Evidence of linear or elliptical polarization has been found at Cornell a few times in the emission of type III bursts. It is no wonder that this type of polarization occurs rarely, because only under very special conditions linearly polarized radiation may be expected to enter into outer space.

As a final remark I should like to recommend as a technique of observation the construction of a multi-element interferometer consisting of aeri-als which accept circularly polarized radiation only. The aeri-als, for instance, might be of the helical type. Using two such instruments, one for right-handed and one for left-handed circular polarization, one would be able to distinguish sources producing right-handed polarized radiation from those showing left-handed polarization. So the oppositely polarized sources contributing to the superposed mixed polarization could be disentangled.

INTERVENTI E DISCUSSIONI

— R. COUTREZ:

Suggests that it might be interesting to compare the polarization at 200 MHz with polarization at much higher frequencies, say at a wavelength of 3 cm.

— A. D. FOKKER:

Remarks that at decimeter-wavelengths the polarization characteristics are fundamentally different from those at meter-wavelengths. It would be worth-while, though, to compare polarizations at, say, 200 and 300 MHz. It does not seem likely that many differences will be found in the state of polarization of noise storms at these two frequencies, but it might be the case for the type IV events.

— J. P. WILD:

Observes that complex polarization behaviour of type IV events need not invalidate the hypothesis of the synchrotron mechanism. If type IV radiation would be emitted as linearly polarized radiation at the source, it might well be observed as unpolarized radiation because of differential Faraday rotation taking place on its way through the corona outwards.

— A. D. FOKKER agrees:

Radiation which is originally linearly polarized might also escape as circular polarized radiation if it is generated in a part of the corona from where only the ordinary magneto-ionic mode is able to escape.

— K. O. KIEPENHEUER:

Asks how strong the magnetic field should be in order that the observed radio emission be circularly polarized.

— A. D. FOKKER:

Says that this depends on the manner in which the electron density and the magnetic field strength decrease with height.

Let the critical frequency be denoted by $f_c = (Ne^2/\pi m)^{1/2}$ and the gyrofrequency by $f_H = eH/2\pi mc$.

If at the level where $Y = f_H/f = 1$ the value of $X = f_c^2/f^2$ is much smaller than unity, polarized radiation has its origin mainly in a region where $Y > 1$ (i.e. $H > 71.5$ G for $f = 200$ MHz, see Fig. 7).

If, on the other hand, the value of Y is much smaller than unity at the level where $X = 1$, polarized radiation is coming from the relatively small region which is bounded by the levels $X = 1$ and $X = 1 - Y$.

There is thus no real lower limit to the magnetic field strength, but the smaller it is, the smaller is the volume from which only the ordinary magneto-ionic component escapes.

Some Notes on Noise Storms.

A. D. FOKKER

Section Ionosphere and Radio Astronomy of Netherlands P.P.T. - The Hague

The occurrence of a noise storm is the most common phenomenon presented by solar radio emission at meter-wavelengths. For this very reason one might almost forget about the fact that very little is yet understood of the mechanism underlying this type of radio emission. Therefore, although everybody is very familiar with the phenomenon of noise storms, a careful study of their properties remains important.

In general we consider as a noise storm the combined occurrence of an enhanced continuum flux level and of a number of shortlived bursts with a duration of less than a second and a bandwidth of a few megahertz. The relative importance of the continuum and of the stormbursts shows great differences. It determines the degree of variability of a given storm. A high speed record of a noise storm is represented by Fig. 1.

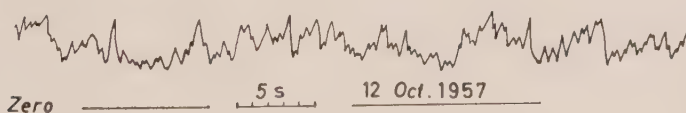


Fig. 1. — Example of a high speed record during a noise storm.

Some authors have suggested that the continuum might be considered as the superposition of a great many individual bursts. From high speed records it is evident that during violent storms the bursts actually overlap each other to a considerable extent. However during many storms there occur periods of some 10 seconds duration, during which the bursts are absent and the intensity remains approximately constant. Still the continuum flux level during such periods is far from being reduced to the quiet sun flux value. Therefore, the continuum and the burst components seem to be clearly distinct from each other, though they apparently are intimately connected.

1. - The beginning of a storm.

The beginning of a storm may be very gradual, but a storm may also start rather suddenly. A gradually beginning noise storm may take $(1 \div 6)$ hours to reach its maximum development. In most cases no special event or situation seems to be related to the development of a storm. Storms generally seem to come into existence « spontaneously ». It should be realized, though, that if we observe a storm to begin, this need not mean that at the same time a disturbance is coming into existence in the corona. It simply may indicate that an already existing noise source at a certain moment for some reason or other becomes « visible » to the terrestrial observer.

In a few rare cases the onset of a noise storm is convincingly related to the occurrence of a flare. In such cases the time of onset is rather sharply defined. It seems that such flare-associated noise storms are definitely different from type IV outbursts.

A period of storminess may have a duration of $\frac{1}{2}$ day up to a few days. There also occur storms with duration of the order of $(1 \div 3)$ hours. These may either be intensifications of already existing noise-activity, or they may occur during periods of calmness. I propose to call them isolated storms.

2. - Noise storms and sunspots.

There is a strong connection between sources of storm radiation and sunspots. A given source is in general observed interferometrically to be situated in the neighbourhood of a particular sunspot group, which it follows in its daily positional shift. The location of a source, though, does not seem to be very stationary with respect to the spot it belongs to, as the daily westward shift occurs in an irregular fashion.

Noise-active sunspots in general are well-developed, belonging to the types *E* or *F*. *G*-sunspots less frequently cause noise-activity and *D*-spots only seldom are noise-active. In the central part of the solar disk we have the following situation:

	Quiet %	Slightly noise-active %	Strongly noise-active %
<i>E</i> -spots	61	23	16
<i>F</i> -spots	44	28	28

Optically there does not seem to exist any difference between sunspots that are noise-active and those that are quiet. It is an easy matter to select

two spots, having very much the same appearance on white light photographs, the one having been noise-active and the other quiet. There also can be given examples of spots that have been observed to develop rapidly from invisible to important spots of the *E*- or *F*-type in a few days. Some of these very soon became noise-active whereas others remained perfectly quiet.

3. - Noise-activity and flare-activity of sunspots.

We say that a sunspot has been flare-active on a particular day if a sufficiently great number* of flares have occurred in the neighbourhood of the spot on the day itself, the preceding and the following day. The situation as regards the relation between flare-activity and noise-activity of spots can be summarized as follows:

Considering only *E*- and *F*-type spots, there is a slight correlation between flare-activity and noise-activity of a given spot on a particular day. But this correlation is largely due to the fact that certain spots aren't active anyway (neither flare- nor noise-active). Selecting now only those sunspots that, when being situated on the central part of the solar disk, have displayed some kind of activity on at least one day, there is left no correlation at all between the days on which the two kinds of activity occur. Noise-activity and flare-activity are just two aspects of sunspot activity in general, but they occur independently of each other.

4. - Distribution of noise-active spots over the solar disk.

Sunspots have a greater probability of being identified as noise-active when near the central meridian than when near the limb. We determined the law according to which this probability changes from the centre towards the limb by considering all spots that have reached the *E*- or *F*-stage of development and those that were identified as noise-active at some day during their period of visibility. We obtained the distribution represented in Fig. 2. The distribution of probability as a function of distance to the centre of the disk is not unlike a cosine law.

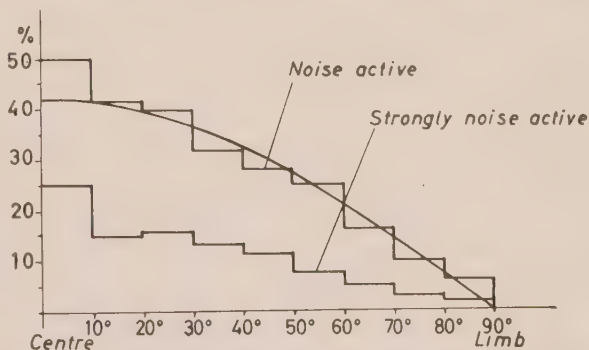


Fig. 2. - Percentages of noise-active sunspots as a function of a distance to the centre of the solar disk.

We note that strongly noise-active spots present about the same type of distribution. This is in agreement with what we found along another line of investigation, *viz.* that there is no appreciable centre-limb variation of the average intensity of noise storms. Very strong noise storms, though, have not been observed to be associated with sunspots near the limb. During their period of visibility sources present a rather constant amount of noise, on the average.

A spot approaching on the eastern hemisphere often is observed to become noise-active from one day to the other. Once it has become noise-active it may continue to be so during a few days in succession.

5. – Height of the noise sources.

Unless a source is situated above a sunspot very near to the limb of the solar disk, it is impossible to evaluate its height. One may try, though, to determine the average height for many sources, if these are situated close to the central meridian. The mean daily shift may be compared with the $13^{\circ}.1/\text{day}$ progression of the sunspots. For greater distances from the central meridian one may make use of the deviation between the sunspot and the noise source

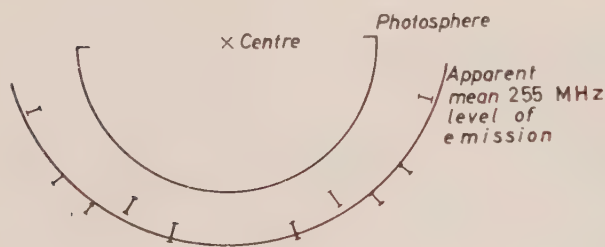


Fig. 3. – Mean apparent level of noise sources at 255 MHz.

position, assuming that on the average the source is situated radially above the spot.

We thus found a mean height of the sources of about 0.38 solar radius at 255 MHz. It is noteworthy that there is found only a small difference in height between sources near the centre of the

solar disk and sources near the limb. The result of five determinations of height is given by Fig. 3.

Thanks to the daily interferometer observations at 169 MHz by the Nançay observatory, it has become possible to compare positions outside the solar limb at two different frequencies, 169 and 255 MHz. Practically always the 169 MHz position is situated farther outside the limb than the 255 MHz position. This is entirely according to expectation. It turns out that on the average the apparent heights of sources at 169 MHz are greater than the source heights at 255 MHz by a factor of about 1.5.

6. - Extent and brightness distribution of noise sources.

An idea about the extent of a source of storm radiation can be obtained from interferometry with a large spacing between the antennas. The greater the extent of a noise source, the smaller will be the interference amplitude relative to the total intensity. From the ratio between them follows the angular diameter of an equivalent circular source of uniform brightness.

At the Nera observatory interferometry is being done with spacings of 390, 570 and 960 wavelengths, at the frequency 200 MHz.

From the observations with spacings of 390 and 570 λ we find source diameters of about 2 to 6 minutes of arc. In general the interference record for

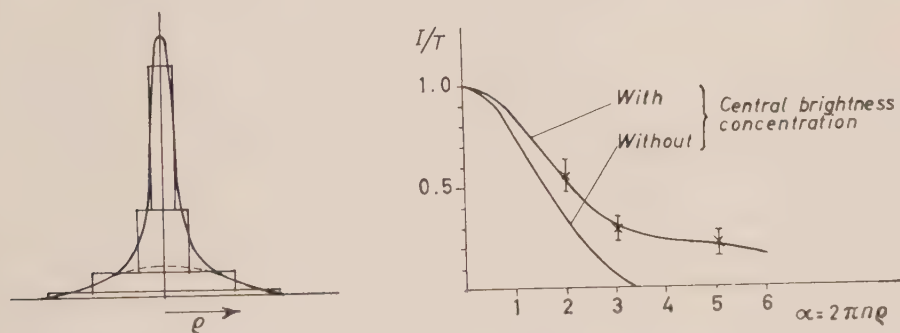


Fig. 4. - Left: Model of the surface brightness distribution over a source (dashed: without central brightness concentration). Right: Corresponding amplitude-spacing curve with a set of observed amplitudes (March 30, 1959) at spacing 388 λ , 572 λ and 960 λ .

the spacing 960 λ does not fit to the amplitude-spacing curve corresponding to a uniform source adapted to the 390 λ and 570 λ observations. The amplitude for the 960 λ spacing being systematically too great, this indicates that there exists an increase of brightness towards the centre of the source. An estimate of the amount of brightness concentration in the centre of the source can be made by looking for a model with a corresponding amplitude-spacing curve (or cosine transform) which fits the three observed points. So we arrive at a model of the type as represented in Fig. 4. The central brightness peaks turn out to be rather steep. Their half brightness width, of the order of 1 to 2 minutes of arc, is smaller than the resolving power of a multi-element interferometer such as the Nançay instrument. It is not unreasonable to assume that the « wings » of the brightness distribution correspond to that part of the radiation which is scattered on its way from the source outwards.

By means of large spacing interferometry we can also determine the order of magnitude of the extent of individual stormbursts. Our observations indi-

cate that the extent of stormbursts too is of the order of a few minutes of arc. The diameters of burst- and continuum sources sometimes are about equal,

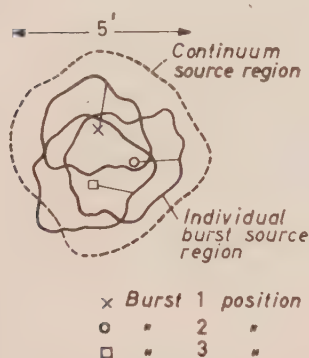


Fig. 5. - Schematic picture of the fine structure of a source of storm radiation.

but the burst sources also may have a smaller extent. With the aid of high speed records one may in addition determine the spread in position of individual bursts.

This spread often is of the order of 1 or 2 minutes of arc. Similar evidence has been obtained at the Mullard Radio Observatory at the frequency 81 MHz with an interferometer spacing of 270λ . These observations have been made in two dimensions (E-W and N-S, HÖGBOM, *Thesis*, 1959). We thus get a picture of the fine structure of source regions as illustrated by Fig. 5. Receiving apparatus which allows the simultaneous recording of the interference and total radiation signals at the three available spacings is now in use at the Nera observatory.

7. - Discussion.

Whether a given well-developed sunspot will be noise-active or not seems to be largely due to accidental circumstances. In general noise activity is displayed only by the more important sunspot groups. This fact might be connected with the presence of magnetic fields of sufficient strength above such sunspots, but one might think as well of the permanent coronal condensations or of the sunspot prominences as providing favourable conditions under which radio noise may be produced.

Maybe every major sunspot group is accompanied by a source of storm radiation. A given spot would only be identified as noise-active if the radiation manages to escape into outer space. The fact that often a sunspot is observed to become noise-active rather suddenly suggests that there existed some kind of screening before that time. A screening action might be thought to be exerted by coronal structures of sufficiently high electron densities.

We note that the height of about 0.4 solar radius at 255 MHz is considerably greater than the height at which the critical electron density is thought to be reached (about 0.1 solar radius). If the stormbursts were due to plasma oscillations they should rather be generated at this lower level. Their radiation in this case would be restricted to a narrow cone of directions.

Now we have seen that the sources of stormbursts have appreciable apparent diameters. It is difficult to imagine, though, how within less than a second

of time such a large region coherently could be excited and de-excited. Therefore one is led to suppose that the angular diameter is largely due to scattering of the radiation by coronal irregularities. If that is true, the apparent height of the sources might indicate the level where most of the scattering occurs rather than the level where the radiation is generated. We must seriously consider the possibility that the source itself of storm radiation is largely hidden.

If then a flare gives rise to a noise storm, we might think that one of the « curtains » hiding an already existing source is somehow removed as a result of the flare action.

Similarly, an isolated noise storm might occur if by any chance somewhere in the coronal cloud cover a « hole » is formed through which the underlying radiation temporarily becomes visible.

APPENDIX

The 4 November 1957 event.

On Nov. 4, 1957 a solar radio event occurred at meter-wavelengths which so far stands out as a unique solar radio phenomenon. It was observed at 169 MHz by the Nançay and Human observatories and at 200 MHz by the Nera observatory.

This kind of event was different both from noise storms and from type IV outbursts. Its peculiar character is especially apparent from the special type of intensity fluctuations. Some fragments are reproduced in Fig. 6. These

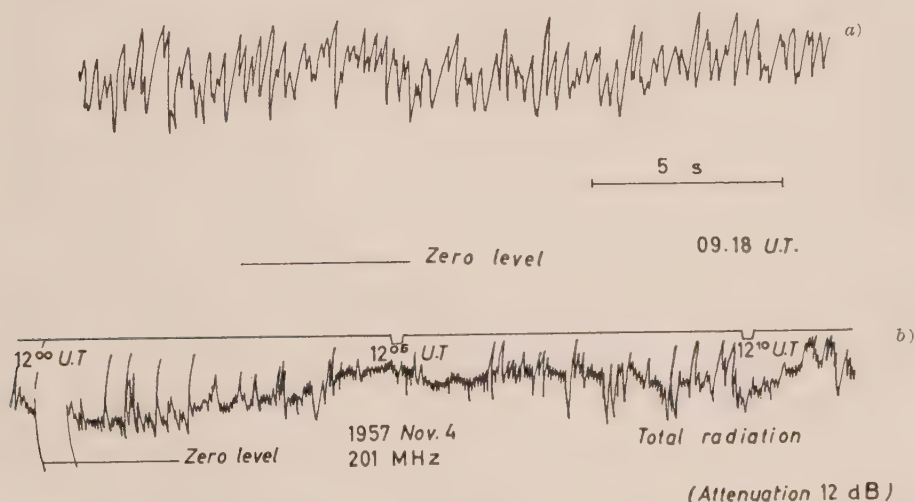


Fig. 6. - a) High speed record of 4 Nov. 1957 event during its early stage. b) Record at a more advanced stage of the 4 Nov. 1957 event.

fluctuations, which were very rapid (about 5 per second), are markedly different from those characteristic for noise storms. Contrary to the case of noise storms, one does not get the impression that a fluctuating component is superposed upon a steady continuum. Instead, the continuum itself seems to have been intensity-modulated. As a matter of fact, the intensity fluctuations are somewhat reminiscent of ionospheric scintillations of radio sources.

For some parts of the event, it would be hard to tell which is the sense of increasing intensity, when isolating the variable part of the record from the rest.

The most striking feature, though, is the fact that there occurred certain dips of intensity which look very much like «bursts in absorption».

The interpretation of the phenomenon is made especially difficult by the complete lack of correlated events: no flares, ionospheric or cosmic ray effects have been observed near the time of beginning of the event. Furthermore, solar radio emission at frequencies above 500 MHz remained undisturbed. Ionospheric scintillation conditions were quiet on Nov. 4.

The source position was in the middle part of the solar disk, where no important sunspots were situated.

At 200 MHz the maximum intensity amounted to about 1000 times the quiet sun flux level.

The event started at about 08.40 U.T. and gradually came to an end at about 15.15 U.T.. It presented a certain kind of evolutionary development. In its later stages the intensity fluctuations became slower and somewhat different in character. The peculiar dips of intensity continued to occur intermittently.

INTERVENTI E DISCUSSIONI

— H. H. RABBEH:

Asks whether there has been found an East-West asymmetry in the distribution of noise-active sunspots.

— A. D. FOKKER:

Says that he has not found a significant East-West asymmetry for strong sources. However, the number of moderately noise-active sunspots seems to be significantly greater on the western hemisphere than on the eastern hemisphere.

— M. MINNAERT:

Remarks that an explanation of the intensity modulations during the 4 November event as some kind of scintillation taking place in the solar corona is not likely to be correct. As a matter of fact, if the layer where irregular refraction takes place is situated close to the source as compared to the distance to the observer, there will be observed hardly any variation of the intensity at all.

— P. SIMON:

Says that at Nançay the event has been observed both with the great interferometer and with a simple radiometer connected to a mirror of 5 metres aperture. The two instruments were situated very close to each other. Though they were tuned at the same frequency with identical band-width, there still were notable differences between the detailed intensity fluctuations as recorded by the two instruments.

— M. MINNAERT:

Suggests that these differences are due to the difference between the antenna patterns of the two antennas.

Mutual differences between the two records might occur if the source region had considerable fine structure, various parts of which were flashing up and down in succession.

— A. D. FOKKER

Says that from two-element interferometer measurements at 255 MHz it appears that the source had a remarkably constant position. The cross-overs of the interference record were so regularly spaced in time, that positional fluctuations certainly have not been greater than ± 0.8 minute of arc about the mean position.

— P. SIMON:

Remarks that the short-period fluctuations had a very small band-width of the order of only 1 MHz. Towards the end of the event Michigan radio spectrograms show a very peculiar spectral feature, consisting of some kind of «spaghetti»-like tiny threads with a band-width of about 1 MHz.

— J. P. WILD:

Notes that a few times extremely weak bursts in absorption during type IV outbursts have been observed with the Dapto spectrograph. He further inquires after the local time at which the Michigan observations have been obtained. He reminds that sometimes anomalous things are observed at low solar altitudes, which must be due to ground reflections.

— P. SIMON:

Says that the Michigan observations began not long after local sunrise.

— K. O. KIEPENHEUER:

Inquires about the spread of radio source positions around the sunspot positions

— A. D. FOKKER:

Answers that this spread is quite considerable. The daily westward shift of radio position from one day to the other may amount to only 5 heliographic degrees, or it may be as much as 20 degrees.

— K. O. KIEPENHEUER:

Wonders whether it would be possible to determine the shape of a particular noise source. The source might have a thread-like structure, as a consequence of which it could be observed to be elongated.

— A. D. FOKKER:

Says that interferometer observations along two, or even several, directions would be needed to settle this question. Such observations have been made so far only at the Mullard observatory at 81 MHz.

— D. J. H. WORT:

Draws the attention to the whistler mode of propagation. As this mode propagates along the magnetic lines of force, certain directional properties of storm radiation might be connected with the magnetic field. He further inquires whether any correlation has been found between noise sources and magnetic fields of sunspots.

— A. D. FOKKER:

Answers that he has not found any correlation, consulting data on sunspot magnetic fields as published by the Crimean Astrophysical Observatory.

The Freiburg Radio Spectrograph. Instrument and Preliminary Results.

H. H. RABBen

Preunhofer Institut - Freiburg i. B.

1. - Description of the instrument.

The radio spectrograph at Freiburg is more or less a copy of the Sydney instrument, however there are some distinct differences. Here a short description:

Receiver. - There are six aerials, each of which feeds one of six R.F.-parts, composed of a three stages amplifier, mixer, and local oscillator. The tuning is done by fourfold capacitors (logarithmic frequency scale), driven by a synchronous motor. Either of two R.F.-parts is connected to one of three I.F.-parts alternatively, and the spectrum is displayed by a treble cathode ray oscillograph, each of the three cathode ray tubes being attached to one of the I.F.-parts. A camera with continuously moving film records a complete spectrum in one uninterrupted line twice per second. The reference sweep-voltage is obtained by a potentiometer, rotating together with the tuning capacitors on a common axis.

Antennas. - The frequency range from 48 to 165 MHz, equally distributed over the six channels, was limited by the standing wave ratio (VSWR) of the aerials. Rhombus antennas could not be used on the Schauinsland (1250 m above sea level) in a climate with much snow and violent gales, causing icings of a thickness up to 30 cm. Thus we had to be content with dipole arrays with plane reflectors, which are weatherproof, but cover a band with a frequency ratio of only 1:1.25, therefore altogether a ratio of 1:3.5, at a max. VSWR of 1.5. The effective areas are nearly equal, varying between 5 and 10 m². Thus the minimum detectable flux density is about $2 \cdot 10^{-21}$ W · m⁻² · Hz⁻¹. The aerials are tilttable mounted on a steel bridge of 30 m in

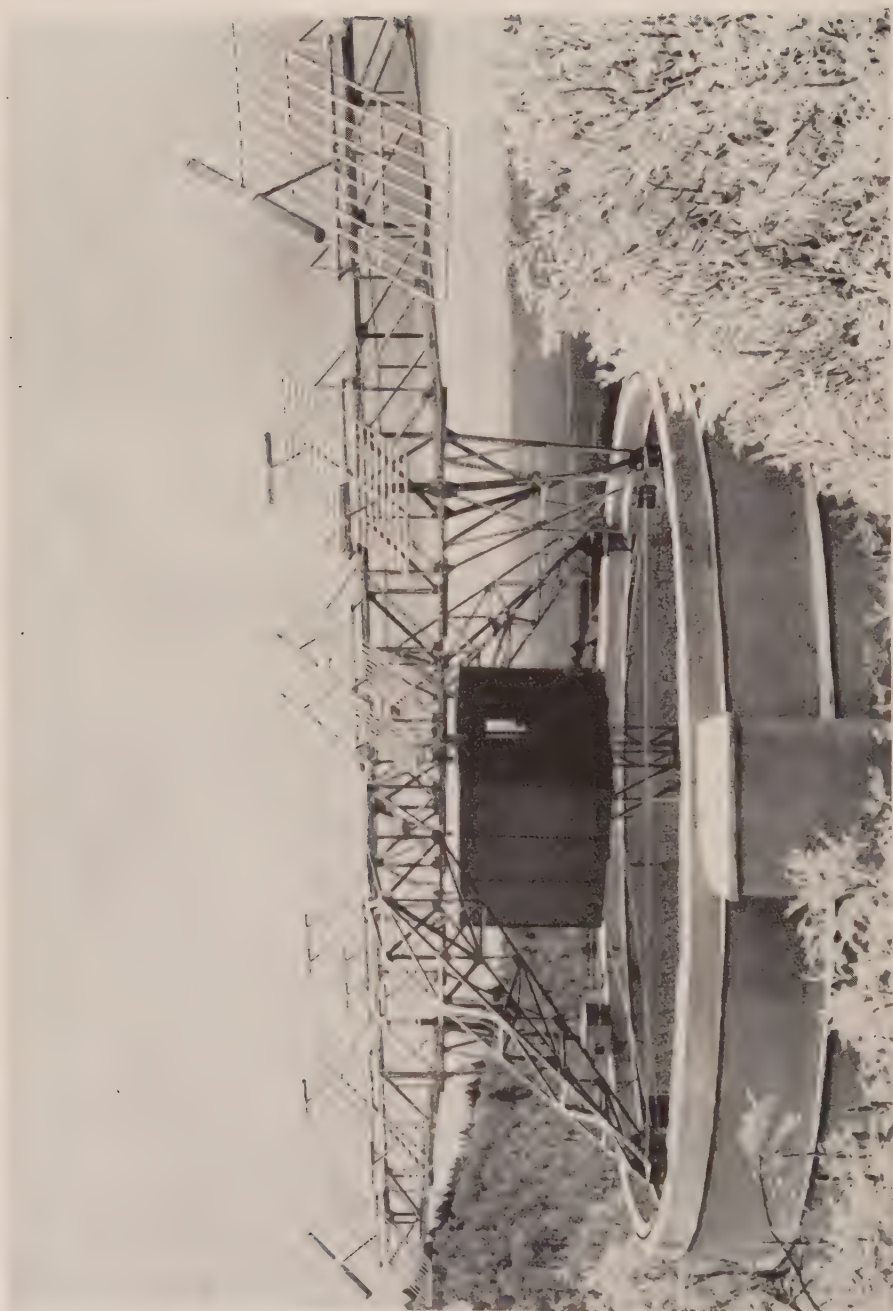


Fig. 1. - The Freiburg radio spectrograph.

length and can be directed to each point in the sky by turning the bridge on a cylindrical tower. The receiver is placed in a little cabin, fixed at the lower side of the bridge, as can be seen in Fig. 1.

Spectrum. — The sweep frequency was fixed at 2 Hz. The bandwidth of 300 kHz and a total time constant of 1 ms result in a number of 390 data per spectrum. Normally, the spectrum is displaced by intensity modulation, but for higher accuracy it can be displayed by switching over to amplitude modulation.

Strong interference is caused by several broadcast and television transmitters. This can not be prevented in middle Europe, but fortunately the recognizability of the solar bursts is not seriously affected.

2. — Preliminary results.

The results, presented here, have been obtained during an investigation of type III bursts, recorded during an observation period of about 220 hours, within the last three months of 1958.

136 events, composed of about 600 bursts, are involved. Their relationship to solar flares is analysed. The study of the bursts' spectrum was extended to shorter wavelengths by incorporating the observations of other stations with single frequency radiometers in the cm-, dm-, and meter-wave-range.

1) *Relation with solar flares.* — In a simultaneous observation period of 200 hours, 96 bursts events and 372 flares occurred.

a) 92 % of the type III events occurred during the life-time ± 5 min of a flare (72 % during the life-time ± 0 min). Other authors found a much lower association.

b) The few events without an observed flare were small (2.5 burst/event).

c) Large burst events occurred preferably at the time of the flare's onset, while the smaller events apparently can occur independently at any part of the flare's life-time.

d) Burst intensity and frequency-drift/s are correlated, *i.e.* a faster drift goes with higher intensity.

e) For burst intensity as well as for frequency-drift/s, no dependence on flare importance could be perceived.

f) The apparent coronal altitude of burst start, computed according to its start frequency, depends on:

- the number of bursts/event (the greater the number, the smaller the altitude of start),
- the burst intensity (the higher the intensity, the smaller the altitude of start),
- and the frequency-drift/s (the faster the drift, the smaller the altitude of start).

2) *Burst efficiency of flares:*

a) Only 22% of the 199 flares were associated with type III bursts. (Imp. 2: 8 flares, Imp. 1+: 22 flares, Imp. 1: 93 flares, Imp. 1—: 76 flares.)

b) These « burst producing » flares occurred only in 21 out of 74 centers of activity (C.A.) with flare occurrence; i.e. most of the C.A.'s had no radio-burst activity because of either no emission, or no escape of radiation (88 radio events included).

3) *Center limb variation:*

a) The probability of burst escape depends on central meridian distance (CMD), and on the hemisphere. The burst radiation shows limb darkening, and a greater absorption on the western hemisphere.

b) Burst intensity as well as frequency-drift/s are likely to be higher for smaller CMD's. This can be understood in terms of a shortening of the time scale (travelling velocity of burst exciting agency close to c !), corresponding to the angle between the direction of the burst path and the line of sight.

The results are of statistical nature and therefore one has to be cautious in applying them to the individual case. During 45% of the observing period, at least one flare was on the sun. If the flare's life-time is increased by ± 5 min, it will be 55%. For this reason, a part of the flare-burst associations could have taken place by chance.

The statistical goodness of fit is somewhat poor because of the small number of events included here. More observations of this kind will have to be made.

A detailed report is published in the *Zeitschrift für Astrophysik* **49**, 61 and 95 (1960).

Eclipse de la Nébuleuse du Crabe.

P. SIMON

Observatoire de Meudon

1. — Données du problème.

Chaque année, aux environ du 15 Juin le Soleil passe à une distance voisine de $5 R_{\odot}$ de la nébuleuse du Crabe. Cette dernière est du point de vue Radio une source d'une certaine étendue (diamètre apparent de $4'.6$ sur 169 MHz) et émettant une énergie de l'ordre de $7.5 \cdot 10^{-24} \text{ W/m}^2\text{Hz}$. Le diamètre apparent et l'énergie reçue de la nébuleuse varient pendant cette « occultation », ce qui peut nous apporter des renseignements sur la structure de la couronne solaire jusqu'à des distances de l'ordre de $20 R_{\odot}$. A titre indicatif notons que sur 169 MHz le flux du « soleil calme » est de l'ordre de $800 \cdot 10^{-24} \text{ W/m}^2\text{Hz}$ et qu'il peut apparaître des centres d'activité dont le flux est de l'ordre de $30\,000 \cdot 10^{-24} \text{ W/m}^2\text{Hz}$.

2. — Les observations.

Les premières observations ont été effectuées avec des interféromètres à permutation de phase à deux antennes. On observe une diminution de franges

du 10 au 20 Juin sur 7.9 m ,

du 11 au 19 Juin sur 3.7 m ,

du 10 au 18 Juin sur 1.9 m .

Depuis 1957 les observations ont été effectuées à Nançay avec un interféromètre à 32 antennes dont le pouvoir séparateur est de $3'.7$, les lobes principaux étant séparés de 2° .

Les observations de Nancay de 1957 et 1958 ont été dépouillées indépendamment par deux observateurs, chacun d'eux utilisant deux méthodes différentes. L'accord entre les résultats a été très bon. Celles de 1959 ont été seulement dépouillées de façon provisoire.

3. — Résultats.

a) On a un élargissement de la source en raison inverse de sa distance au soleil, mais cet élargissement qui porte son diamètre de $4'.6$ à $16'$ n'est pas symétrique (plus grand lorsque la source est à l'ouest du soleil) il commence à au moins $15 R_{\odot}$.

b) La densité de flux augmente quand la source s'élargit.

c) Les variations de position du centre de la source sont inférieures à la minute d'arc.

d) Si l'élargissement de la source est assez régulier, les variations de densité de flux sont très irrégulières, même si l'on tient compte de la variation du cycle.

4. — Discussion.

a) Les variations de diamètre sont en bon accord avec les autres observations.

b) Les variations de flux sont compatibles avec les autres observations surtout si l'on tient compte des autres procédés d'observation.

c) On peut penser que des irrégularités du phénomène sont observées ailleurs.

5. — Conclusion.

Pour rendre compte de ces observations, il faut imaginer un milieu diffusant et en même temps réalisant une certaine focalisation de l'énergie.

INTERVENTI E DISCUSSIONI

— M. MINNAERT:

A-t-on comparé les formes de la couronne pendant la durée de la manipulation?

Car nous voyons par ex. que le 10 et le 20, journées symétriques par rapport à l'éclipse, les formes de la nébuleuse sont nettement différentes.

— P. SIMON:

HEWISH explique ces différences en partant du champ magnétique du soleil. Dû à l'inclinaison de l'axe du soleil sur le plan de l'ecliptique, on voit qu'il y a une notable différence entre ce qui se passe par ex. le 16 et le 14 pour la Crab nebula.

— M. MINNAERT:

Ceci est probablement l'allure générale et moyenne des champs. Mais on pourrait regarder l'image individuelle.

— P. SIMON:

Probablement. Ce qui frappe, c'est l'irrégularité. D'autre part — d'après une correspondance de BOISCHOT — il semble que le Dr. FIROR au cours de ses observations — au moment où ses franges avaient complètement disparu — les a vu réapparaître pendant sensiblement une heure.

— G. RIGHINI:

Est-ce qu'on pourrait — avec un peu de fantaisie peut être — trouver dans ce diagramme là (le diagramme de la puissance reçue de la Crab nebula en fonction du temps) deux maximums?

— P. SIMON:

C'est ce que BOISCHOT avait tenté. Mais le nombre de points est insuffisant pour qu'on puisse affirmer quelque chose.

— G. RIGHINI:

Est-ce que vous observez la source tout le long de l'année? Est-on sûr qu'elle n'a pas de fluctuation... naturelle?

— P. SIMON:

Les variations pendant l'eclipse sont tout de même extrêmement importantes. Et nous avons un certains nombre d'observations en dehors de l'eclipse qui montrent une constance de la source.

— C. DE JAGER:

En conclusion je dirais qu'on peut très bien l'utiliser en ce qui concerne la mesure des diamètres, mais qu'on devrait être très prudent en ce qui concerne les mesures d'intensité.

Il est bien entendu que vos mesures aujourd'hui ont parfaitement confirmé les vieux calculs de Link.

— P. SIMON:

Le problème c'est que d'après les calculs de Link, il y aurait un déplacement de la source. Tandis qu'il est difficile de le mettre en évidence, compte tenu du fait que vue la forme de la source sa position est un peu imprécise. On peut affirmer en tout cas que le déplacement en angle horaire est inférieur à 3' d'arc.

— M. MINNAERT:

Ceci est décrit comme ayant lieu à une heure déterminée de la journée. Hors pendant la journée, la sphère celeste tourne, et c'est comme si on l'observait dans différentes directions, avec des lobes et un pouvoir séparateur différent.

— P. SIMON:

Nous n'avons pu malheureusement effectuer ce genre d'observation, notre interféromètre étant essentiellement un instrument méridien. Disons qu'il permet une heure d'observation sur une dizaine de franges. On pourrait comparer ces franges entre elles pour voir leurs différences.

Quoiqu'il y ait des incidents (parasites...). Mais HEWISH a fait des observations avec un interféromètre NS et EW et il donne une espèce de forme de la nébuleuse du Crabe.

— R. COUTREZ:

Je puis vous demander si vous avez une explication de l'asymétrie de la courbe?

— P. SIMON:

Peut être est elle liée à l'inclinaison de l'axe du soleil et des champs magnétiques qui lui sont liés. J'ai d'ailleurs l'impression que cette année cette disymétrie est moindre. Mais il y a à faire le dépouillement soigneusement...

— K. O. KIEPENHEUER:

Pour une comparaison optique radio, il y a très peu d'espoir, parcequ'on se trouve toujours à quatre rayons du soleil, où l'on ne peut avoir d'observation coronale optique. Même à Sacramento Peak, on ne dépasse pas un rayon.

— M. MINNAERT:

Mais cependant les maxima de la raie verte ou jaune ne donneraient ils pas des indications, même à une grande distance?

— K. O. KIEPENHEUER:

Extrapoler serait un peu dangereux.

Quelques remarques sur les types IV.

P. SIMON

Observatoire de Meudon

Toutes les observations que nous avons utilisées ont été effectuées à fréquence fixe soit par mesure du flux global, soit en utilisant des interféromètres à deux ou à multiples antennes. Avec ces moyens nous avons essayé de préciser un certain nombre de points concernant les propriétés des types IV et leurs relations avec un certain nombre d'autres phénomènes.

1. — Identification des types IV.

Leur première identification a été effectuée à partir de mesures interférométriques, ce qui ne peut se généraliser. Mais si l'on considère les « bons » types IV, on remarque qu'ils sont toujours liés à de gros sursauts centimétriques ou décimétriques. On a donc choisi un critère d'énergie tel que la relation inverse puisse être toujours vérifiée. En adoptant les critères suivants: sursaut d'une durée supérieure à 10 minutes et intensité maxima du flux supérieure à $50 \cdot 10^{-21} \text{ W/m}^2 \text{ Hz}$ sur 9400 MHz ou à $30 \cdot 10^{-21} \text{ W/m}^2 \text{ Hz}$ sur 3000 MHz, il semble bien que l'on voit toujours le type IV apparaître sur 169 MHz. En utilisant cette généralisation qui permet une identification facile des types IV on a pu dresser une liste de 128 types IV pour la période Juin 1956-Juin 1958. Il nous semble qu'une telle liste est plutôt limitative et laisse échapper un certain nombre d'événements qui sont probablement des types IV.

2. — Centres optiques donnant les types IV.

23% des types IV sont liés à des éruptions d'importance 1, 47% à des éruptions d'importance 2; et 30% à des éruptions d'importance 3. Si l'on part des éruptions, on voit que les types IV sont plutôt liés aux éruptions les plus importantes du point de vue optique.

Les centres d'activité correspondants ont donné parfois plusieurs types IV successivement, jusqu'à 4 ou 5 pendant leur passage sur le disque. Il semble même qu'il existe sur le soleil des régions privilégiées où pendant plusieurs rotations on peut observer des centres d'activité donnant des types IV.

3. – Propriétés du type IV sur ondes centimétriques.

Avant l'apparition du type IV, la condensation centimétrique présente une augmentation d'intensité, limitée à une région très étroite et très fortement polarisée. A la précision des mesures, il semble que ce soit sur cette condensation que se forme le type IV, soit à une altitude très probablement de l'ordre de 20 à 30 000 km. On n'observe aucun déplacement de la source comparable à celle observée sur ondes métriques, même sur le limbe.

Si l'on prend un cas typique (23 Mars 1958), il semble exister une source étroite fortement polarisée et d'intensité constante pendant tout le sursaut, accompagnée d'une source plus large, fournissant la principale contribution aux fluctuations d'énergies observées. Si l'on porte l'énergie totale reçue (flux · temps) on n'observe aucun effet de directivité en fonction de la distance au centre de disque.

4. – Les types IV et les relations solaires terrestres.

a) *Effets ionosphériques.* Dans 94 % des cas, on observe des SID.

Tous les « black out polaires » observés soit en terre Adélie, soit au Canada correspondent à des types IV de grande énergie observés généralement quelques heures auparavant. Il semble cependant que dans certain cas le délai soit plus long.

b) *Effets géomagnétiques.* Les types IV correspondant aux éruptions les plus importantes sont étroitement corrélés aux orages géomagnétiques les plus importants.

c) *Rayons cosmiques.* Le type IV du 23 Mars 1958 a donné une augmentation du rayonnement cosmique observé à des altitudes de l'ordre de 30 km et à de hautes latitudes (étude effectuée par WINCKLER). Celui du 22 Août 1958 a donné un effet du même genre étudié par ANDERSON.

5. – Types IV et activité métrique (storms de types I).

Les types IV se produisent généralement pendant les périodes où l'on observe des centres d'orage. Si l'on mesure la distance apparente entre le centre optique donnant le type IV et les centres d'orage, on trouve que dans 80 %

des cas, après un type IV, cette distance est inférieure à 6'. D'ailleurs quand le type IV est observé à l'interféromètre métrique, on peut parfois voir la formation d'un orage, une ou deux heures après le début du type IV, à des distances parfois assez grandes. Son flux « bursté » se superpose alors au flux du type IV sur un enregistrement global.

6. — Eruptions et orages.

Cette relation a été étudiée pour la période Mars 1957-Août 1958. On a retenu seulement les 100 débuts d'orage ou augmentations de niveau dont on était assuré de mesurer la position à l'interféromètre. On a recherché s'il existait une éruption d'importance 1 ou plus observée dans les 2 heures qui précèdent le phénomène radio. Dans 6 cas, il n'y a pas d'éruption, mais pour 3 d'entre eux la position radio est sur le limbe Est du soleil. Dans 33 cas on a seulement 1 éruption, dans 61 cas plusieurs éruptions.

a) Le délai est assez variable entre l'éruption et le phénomène métrique.

b) Dans 80 % des cas, la distance apparente entre les deux phénomènes est inférieure à 6', alors que la proportion n'est que de 45 % pour une épreuve test correspondant à des éruptions prises au hasard.

c) Si l'on cherche les éruptions qui se sont produites dans les deux heures qui suivent l'événement radio, dans 28 % des cas on n'a pas d'éruption, pour les autres cas la distribution est analogue à celle trouvée pour les éruptions observées avant l'événement radio.

On peut conclure qu'il existe une corrélation dans le temps et dans l'espace entre les événements radio considérés et les éruptions de certains centres d'activité. On peut représenter géométriquement cette relation et grouper par fuseau solaire les observations. Si l'on interprète la ligne joignant le phénomène optique au phénomène radio comme une ligne de propagation de l'énergie, on remarque un effet de réfraction très grand.

7. — Observation des « noisy spots ».

Les données statistiques publiées par BOIRSCHOT sont parfaitement confirmées après trois années ininterrompues d'observation. Pour 1 150 taches, les diamètres apparents se répartissent uniformément entre les valeurs de l'ordre de 1' et 9'. Des centres larges peuvent apparaître sur le limbe, mais en général les taches du limbe sont plutôt étroites. Par contre la distribution des taches et de leur intensité en fonction de leur distance du centre du disque fait ap-

paraître un effet important de directivité. Rappelons qu'il apparaît de grandes différences d'une tache à l'autre: en particulier les taches étroites sont généralement formées presque exclusivement d'un continuum, alors que les taches larges sont généralement très « burstées ».

Les taches « tournent » très mal: les observations de l'interféromètre Nord-Sud vont peut-être permettre de donner une solution à ce problème: d'après les observations effectuées depuis 4 mois il semble que l'effet de directivité soit beaucoup plus étroit que ne l'indique la statistique: si l'on tient compte de la position en latitude, on a pu identifier 34 centres distincts: 26 ne sont observés qu'un seul jour, 6 le sont 2 jours et les 2 qui sont observés 3 jours n'ont pas une altitude constante. Pour les taches observées deux jours de suite, les altitudes peuvent être évaluées: elles sont régulièrement réparties entre 1.1 et 0.3 $R_{\odot}$. Il semble donc se confirmer que l'activité métrique est liée à la formation successive ou simultanée de plusieurs centres d'activité.

8. – Sursaut tenant du type IV et de l'orage.

Si l'on caractérise l'orage par l'étroitesse de son spectre, son caractère « bursté » et sa relation lâche avec les éruptions, le type IV par la largeur de son spectre, son caractère « doux », sa relation étroite avec les éruptions les plus importantes, il faut noter qu'il existe une émission de caractère intermédiaire, à spectre relativement large, mais ne descendant pas jusqu'au centimétrique, ayant un lien étroit avec les éruptions importantes: on propose de l'appeler orage-continuum.

9. – Conclusion.

Peut être peut-on trouver une continuité dans les caractères des émissions, depuis les émissions à très large bande comme les types IV jusqu'aux émissions à spectre très étroit comme celle du 4 Novembre 1957.

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INTERVENTI E DISCUSSIONI

— A. D. FOKKER:

Il existe une certaine corrélation entre les centres d'activité, les sursauts, etc., je pense donc qu'il faut être très prudent dans ce genre de corrélation et surtout dans l'interprétation physique que l'on pourrait en faire.

— P. SIMON:

Le but de cette étude est précisément de préciser cette corrélation.

— F. BACHELET:

Il y a un problème d'identification des types IV: ici on en trouve 128, alors que MACLEAN pour un temps plus long n'en a retenu que 10. Je voudrais demander au professeur WILD d'où vient cette asymétrie.

— J. P. WILD:

Tout d'abord les spectrographes sont moins sensibles, de sorte que nous n'avons que les gros événements; deuxièmement, le type IV est un événement rare sur ondes métriques; troisièmement MACLEAN s'est astreint à ne retenir que les événements parfaitement isolés et définis sans ambiguïté. Le type IV est essentiellement un phénomène des courtes longueurs d'ondes.

— F. BACHELET:

Doit on être prudent pour accepter cette liste ou non?

— P. SIMON

En fait sur les 128 types IV ainsi déterminés, je n'en ai retenu que 24, d'après leur importance optique, pour établir une corrélation avec l'activité géomagnétique.

— M. MINNAERT:

N'y a-t-il pas une possibilité de vérifier cette liste pour les événements observés aussi avec le spectrographe australien?

— P. SIMON

Nous sommes en train de le faire avec les observations effectuées en Australie mais à fréquence fixe.

— K. O. KIEPENHEUER:

Vous parlez de régions dont l'activité persiste pendant un an: est-ce qu'il s'agit de l'activité générale ou de celle en type IV? Comment l'avez vous localisée?

— P. SIMON

Il s'agit bien de l'activité en types IV. La localisation est assez large et porte sur des fuseaux solaires de 30°: en fait il s'agit seulement d'une tendance.

Radio-Observations of the Sun at Microwave Frequencies

H. TANAKA

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There are three main stations of radio astronomy in Japan. At Toyokawa, a station which belongs to the Nagoya University, observations of solar radio emission at microwave frequencies ranging from 1000 to 9400 MHz are now being made. We have 4 radiometers and two 8-element interferometers.

1. - Equipment.

First, we have 4 radiometers at frequencies of 1000, 2000, 3750 and 9400 MHz [1]. All the paraboloids are made in similar figures having the aperture angle of 80 degrees, and all the antenna feeds at the focus are made also in similar figures (TE₁₁ circular waveguides). The gain of each antenna was calculated by choosing one of them (3750 MHz) as a standard. In this case, we have taken into consideration the degree of disturbance due to the antenna feeds, which has the value of about 15 to 25%. In practice, these values are estimated by placing similar obstacles close to the antenna feeds. Of course the estimation of disturbance is not accurate but the observed values at these frequencies may have the relative accuracy of about $\pm 10\%$. Careful attention is being paid in order to keep the excellent accuracy of observation for a long period. For example, the observations at 3750 MHz have been made for about 8 years and if you compare these values to those of Ottawa at 2800 MHz, you will find an excellent correlation between these values, though a yearly drift can be perceived probably due to the difference of frequency [2]. The relative accuracy of observation at both stations may be at least $\pm 3\%$. This correlation is still better than that taken between 3750 and 9400 MHz of our own station. But now it has become clear from the observations by two interferometers that the brightness distri-

butions at these two frequencies are not quite similar but somewhat different from spot to spot.

All the radiometers have also devices for measuring circular polarization. The way of measuring circular polarization on centimeter waves (3750 and 9400 MHz) is shown in Fig. 1a). Two circular components are changed into two linear ones by a $\lambda/4$ plate, then the plane of polarization is changed by ± 45 degrees after passing through a ferrite switch and, because only one sense of polarization is allowed to enter the waveguide, we have a modulated signal at the

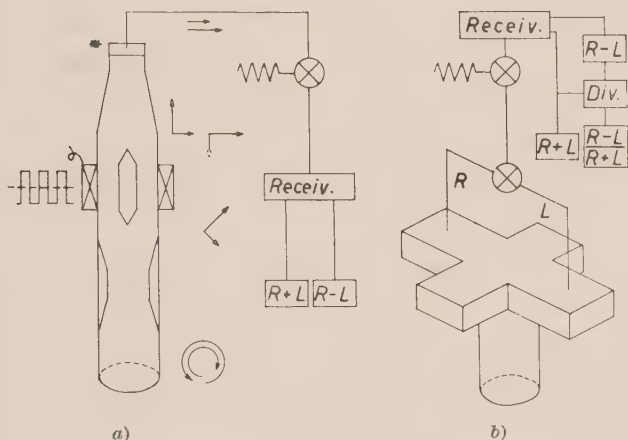


Fig. 1. — Methods of measuring circularly polarized components: a) for 3750 and 9400 MHz, and b) for 1000 and 2000 MHz.

output corresponding to $R - L$. After this modulation, we have an additional ferrite switch for Dicke's modulation for recording $R + L$. On decimeter waves (1000 and 2000 MHz), we are using another method as shown in Fig. 1b). We know that a turnstile circuit can separate two circular components in two lines. We take these signals one after another and then we have another switch for Dicke's modulation. Here we use mechanical switches using a rotating disk. On these wavelengths, the change of flux during the bursts is rather complicated, so we record $R + L$ and $(R - L)/(R + L)$ instead of recording $R - L$ using electronic dividers.

Then we have two 8-element interferometers at frequencies of 4000 [3] and 9400 [4] MHz. The former is constructed in 1953 and we started construction without knowing Christiansen's interferometer. The latter is constructed in April 1959. Each aerial spacing is 86λ , and they have half-power widths of 4.5 minutes of arc near the meridian. All the aeri-als have equatorial mounting so that observations can be made for more than 5 hours every day. These aeri-als have also devices for measuring circular polarization. For the one at 4000 MHz, hand-operated $\lambda/4$ parallel plates are mounted ahead of

paraboloids. With the other at 9 400 MHz, ferrite switches are used so that two series of drift curves, each for $R+L$ and $R-L$, can be obtained simultaneously.

2. - Some recent results.

(A) *Slowly varying component (coronal condensation).*

1) The ratio of the slowly varying component to the base component has its maximum at about 5 000 MHz [5].

2) The size of coronal condensation is almost the same as that of calcium plage, though at 1 000 MHz, the outline is rather indistinct [6, 7].

3) The condensation seems to extend to a height of about $0.1R_0$ at these frequencies. According to the method proposed by Dr. MATHEWSON, that is, the method of determining the center of the active region from the relative motion towards the optical spot around the central meridian, the active center seems to be at a height of about 10 000 km over the photosphere. But if the apparent active center might move slowly backwards due to the change of balance of extraordinary waves, as will be mentioned later, there would be a certain probability of underestimation. On the other hand, interferometric obser-

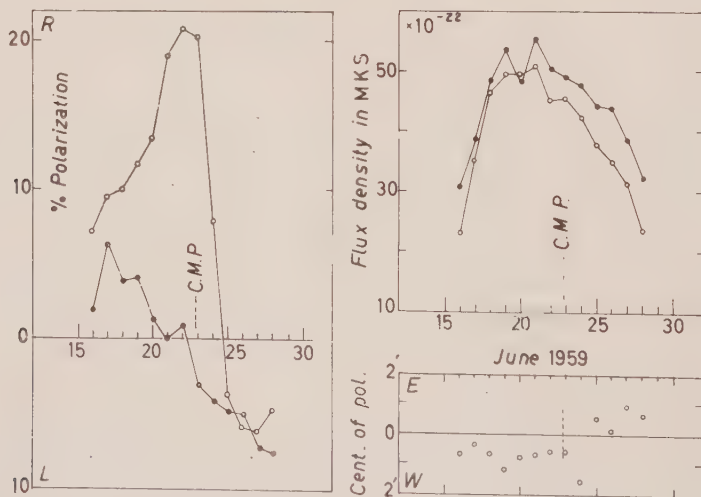


Fig. 2. - An example of the results of observation by two 8-element interferometers^s showing different features of polarization between 4 000 and 9 400 MHz as well as bipolar structure of the source of polarization. «Center of Polarization» shows the angular deviation of peaks on the polarization-drift curve to the peaks on the intensity-drift curve. Open circles are for 9 400 MHz and closed circles are for 4 000 MHz.

vations as well as eclipse observations (19 April 1959) [7] show that there is some amount of condensation at least up to the height of about 70 000 km.

4) According to the eclipse observations [7], the source of polarization is strictly confined in a small area over the sunspot. There are two small sources of different sense of polarization over the bipolar sunspot group, each corresponds to the sense of the extraordinary wave.

5) It is also found by the eclipse and interferometric observations that, at this frequency range, the higher the frequency the larger the percentage of polarization of this small area, which sometimes reaches 60% at 9 400 MHz.

6) Some sources have a different balance of polarization between 4 000 and 9 400 MHz. This was found directly by our eclipse observations, which was also confirmed by recent observations using two interferometers. In Fig. 2, you can see one example where the value of $R - L$ of this radio spot changed its sense of polarization on different days. This may suggest that the foregoing part of this spot has larger electron density than the other. It must be added, however, that there are many cases where this balance changes near the limb or even does not change at all.

7) By combining these results, we are attempting to build a model as shown in Fig. 3. The frequency spectrum of flux density for each spot may be explained by assuming an average temperature of the order of $2 \cdot 10^6$ °K

and an average electron density of the order of $5 \cdot 10^9$ cm⁻³. In these circumstances, the magnetic field must have a value of about 1 000 G to explain 60% of polarization at 9 400 MHz. But in such a case, the polarization at 4 000 MHz should be larger than at 9 400 MHz. To explain this contradiction, we must assume a higher



Fig. 3. — Tentative model for a coronal condensation.

electron density over the sunspot.

(B) Bursts.

1) Bursts which increase their intensity towards high frequencies have a good correlation with SID, while those which have an opposite tendency have a good correlation with magnetic storms (Hiraiso group).

2) The sense of polarization of bursts has no definite correlation with the position of the source on the sun except that, at 9 400 MHz, a slight tendency can be perceived which is similar to the relation connected with a slowly varying component [8]. This may suggest that the source is very small.

3) There are many bursts that reverse their sense of polarization at frequencies around 3 000 MHz, and some bursts reverse their sense even with

time [8]. These may suggest the existence of some declined sources or their movements from one spot to the other.

4) Linear polarization could not be found at 3750 MHz with a band width of 10 MHz [5].

5) Even for the most intense burst occurred near the limb, the position of the source did not change during the burst, and the size was about 3 minutes of arc which was calculated from the fringes of the side-lobes [2].

* * *

Finally, I should like to conclude by expressing that of all the observations the responsibility is mine, but most of the discussions are mainly due to my colleague T. KAKINUMA.

APPENDIX

News from the Tokyo station.

At the Tokyo station, they have an interferometer for locating sources of bursts at a relative accuracy of 8 seconds of arc. Four records are taken for each pair of the aerial, which correspond to four fringes each $\pi/2$ radians apart. These fringes follow the sun automatically.

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INTERVENTI E DISCUSSIONI

— P. SIMON:

How much is the wavelength of the interferometer at Tokyo?

— H. TANAKA:

200 MHz.

— G. ELSTE:

How many examples have you as to the result (4), 6)?

— H. TANAKA:

Direct measurements are still 3 or 4, but statistical observations show that such cases are not rare.

— H. H. RABBen:

You have shown the relation between polarization and position of radio spots. Have you measured the relation directly?

— H. TANAKA:

Yes.

— J. P. WILD:

As to the interferometer at Tokyo, I think that the accuracy of 8 seconds of arc is hard to believe.

— H. TANAKA:

I do not know the detail. A paper is now in press.

— J. P. WILD:

Tell me the principle of the electronic divider.

— H. TANAKA:

When $R+L$ increases, the gate for $R-L$ opens at a short time-rate. Details are shown in [1].

Introduction to the Theory of Synchrotron Radiation.

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1. -- It is well known that an accelerated point charge, in particular an electron, emits electromagnetic radiation, the power emitted being given by the Larmor formula

$$(1) \quad W = \frac{2e^2}{3c^3} \left(\frac{d\mathbf{v}}{dt} \right)^2.$$

Here e designates the charge, c the velocity of light, $\mathbf{v}$ the velocity of the charge, and t the time. Formula (1) is valid in the rest system of the charge, *i.e.* for a vanishing small velocity. In practice it holds good in the non-relativistic field, or when the velocity is small with respect to c .

The energy radiated by a non-relativistic electron according to (1), is generally very small compared with the kinetic energy and brings about a nearly negligible correction to the equation of motion. This accounts for the comparatively long life-time of an electronic oscillator in free space.

However, the situation is radically changed in the relativistic case, *i.e.* when the electron acquires a kinetic energy which is comparable to, or much greater than, its rest energy (0.51 MeV). In this case the energy radiated is not at all negligible and must be taken into account. These facts began to attract the attention of physicists [1] especially when the high energy machines such as the betatron and the synchrotron gave the possibility of accelerating the charged particles to ultrarelativistic velocities. Several authors dealt with the theory of synchrotron radiation [2](*). It was soon realized that the same phenomenon could account for some of the radio emission from celestial bodies [3].

(*) See references in: D. IVANENKO and A. SOKOLOV: *Klassische Feldtheorie* (Berlin, 1953), p. 184.

2. — The relativistic generalization of (1) is readily found by an argument due to SCHWINGER. If we denote by $d\varepsilon$ the energy radiated during the time interval dt , we have $W = d\varepsilon/dt$. As is well known, $id\varepsilon/c$ is the time component of a four-vector, whose space components are represented by the momentum $d\mathbf{p}$ of the emitted radiation. In the rest system of the electron the radiation emitted is dipole radiation and $d\mathbf{p} = 0$ for symmetry. Therefore in the rest system of the electron (with the origin on the electron) both $d\varepsilon$ and dt are time components of purely timelike vectors and under a Lorentz transformation transform in the same manner. Precisely, they are simply multiplied by the same coefficient $1/\sqrt{1-\beta^2}$.

Consequently, $W = d\varepsilon/dt$ must be an invariant. Our task is then to find an invariant, which for $v > 0$ reduces to the expression (1). First by introducing the momentum $\mathbf{p}$ of the electron, we write (1) in the form

$$(2) \quad W = \frac{2}{3} \frac{e^2}{m^2 c^3} \left(\frac{d\mathbf{p}}{dt} \right)^2$$

since in the rest system $d\mathbf{p} = m d\mathbf{v}$, where m represents the rest mass of the electron. Then we note that the momentum $\mathbf{p}$ and the energy E of the electron form a four-vector $(\mathbf{p}, (i/c)E)$ and the same will be true of $d\mathbf{p}$ and dE (*). Consequently, $(d\mathbf{p})^2 - (dE)^2/c^2$ is invariant. In the rest system of the electron this invariant tends to $(d\mathbf{p})^2$ since $d\mathbf{p}$ tends to $m d\mathbf{v}$ while dE tends to $m(dv)^2/2$ (kinetic energy), i.e. to an infinitesimal of higher order.

On the other hand the proper time $dt \sqrt{1-\beta^2}$ is an invariant which in the rest system becomes equal to dt . This shows that the relativistic generalization of (2) is

$$(3) \quad W = \frac{2}{3} \frac{e^2}{m^2 c^3} \frac{1}{1-\beta^2} \left[\left(\frac{d\mathbf{p}}{dt} \right)^2 - \frac{1}{c^2} \left(\frac{dE}{dt} \right)^2 \right] = \frac{2}{3} \frac{e^2}{m^2 c^3} \left(\frac{E}{mc^2} \right)^2 \left[\left(\frac{d\mathbf{v}}{dt} \right)^2 - \frac{1}{c^2} \left(\frac{dE}{dt} \right)^2 \right],$$

where use has been made of the relation $E = mc^2/\sqrt{1-\beta^2}$.

3. — As is well known, a charged particle with constant velocity v perpendicular to a magnetic field $\mathbf{B}$ (**) is forced to move in a circle whose radius is given by (**)

$$(4) \quad a = \frac{m v c}{e B \sqrt{1-\beta^2}} = \frac{\beta E}{c B}.$$

(*) The difference of two four-vectors is obviously a four-vector.

(**) We will denote by $\mathbf{B}$ the accelerating magnetostatic field while the radiated magnetic field will be denoted by $\mathbf{H}$.

(***) See for instance: M. S. LIVINGSTON: *High-Energy Accelerators* (New York, 1954), p. 20.

Hence the angular velocity will be

$$(5) \quad \omega_0 = \frac{eB\sqrt{1-\beta^2}}{mc} = \frac{eBc}{E}.$$

For such a particle we shall have

$$(6) \quad \left(\frac{d\mathbf{p}}{dt}\right)^2 = \omega_0^2 p^2 = \frac{e^2 B^2 c^2}{E^2} p^2$$

and, since v is constant, $dE/dt = 0$.

On the other hand

$$(7) \quad p^2 = \frac{m^2 v^2}{1-\beta^2} = \frac{m^2 c^2}{1-\beta^2} \frac{v^2}{c^2} = E^2 \frac{\beta^2}{c^2}.$$

Upon substitution of (6) and (7) into (3) we get

$$(8) \quad W = \frac{2}{3} \frac{e^4 B^2 \beta^2}{m^2 c^3} \left(\frac{E}{mc^2}\right)^2.$$

This formula shows that in a given magnetic field slow electrons ($E \approx mc^2$) radiate a power proportional to the kinetic energy (β^2), while very fast electrons ($\beta \approx 1$) radiate a power proportional to E^2 . For an ultrarelativistic electron one can deduce

$$(9) \quad W_{(\text{watt})} = 1.8 \cdot 10^{-21} B_{(\text{gauss})}^2 E_{(\text{McV})}^2.$$

which is a useful numerical formula.

4. — In order to obtain more detail about the radiation we will evaluate the vector potential in the wave zone. The vector potential $\mathbf{A}$ satisfies the differential equation

$$(10) \quad \nabla^2 \mathbf{A} - \frac{1}{c^2} \frac{\partial^2 \mathbf{A}}{\partial t^2} = -\frac{4\pi}{c} \mathbf{J},$$

where $\mathbf{J}$ represents the current density. By taking as Green function $\delta(t' - t + r/c)/r$ and applying standard methods it is possible to show that the solution of (10) due to the source $\mathbf{J}$ (i.e. apart from a surface integral due to the contribution of other sources) is given by

$$(11) \quad \mathbf{A}(\mathbf{P}, t) = \frac{1}{c} \int \frac{1}{r} \mathbf{J}(\mathbf{P}', t') \delta(t' - t + r/c) dV_{\mathbf{P}'} dt',$$

where $r = |\mathbf{P} - \mathbf{P}'|$.

Now, in the case of a point electron located at $Q(t)$ and moving with velocity $\mathbf{v}(t)$, we have $\mathbf{J}(P', t') = e\mathbf{v}(t')\delta(P' - Q)$. Upon substitution into (11), we get

$$(12) \quad \mathbf{A}(P, t) = \frac{e}{c} \int \frac{1}{r} \mathbf{v}(t') \delta(t' - t + r/c) dt'.$$

Note that $r = P - Q(t')$ is now a function of t' . For this reason, the integration with respect to t' is not so straightforward as it might appear and would lead to the Lienard-Wiechert potential.

5. — We will refer to spherical co-ordinates $\varrho, \vartheta, \varphi$, taking as axis ($\vartheta = 0$) the axis of the circle described by the electron. The co-ordinates of point Q will be $\varrho = a$, $\vartheta = \pi/2$, $\varphi = \omega_0 t'$, while those of the fixed point P will simply be called $\varrho, \vartheta, \varphi$. We will be interested in the wave zone, where ϱ is very large compared to all other lengths of interest. It is then an easy matter to find that, apart from quantities which go to zero when $\varrho \rightarrow +\infty$, we have

$$(13) \quad r = \varrho - a \sin \vartheta \cos(\omega_0 t' - \varphi) = \varrho - a \sin \vartheta \sin \alpha,$$

with the position

$$(14) \quad \alpha = \omega_0 t' - \varphi + \pi/2.$$

By substituting into (12), we find as the approximation valid in the wave zone

$$(15) \quad \mathbf{A}(P, t) = \frac{e}{c\varrho} \int \mathbf{v}(t') \delta\left(t' - t + \frac{\varrho}{c} - \frac{a}{c} \sin \vartheta \sin \alpha\right) dt'.$$

Now, by recalling that, within any interval 2π which includes $x = 0$, the formula is valid

$$(16) \quad \delta(x) = \frac{1}{2\pi} \sum_n^{+\infty} \exp[inx]$$

and that $\delta(cx) = \delta(x)/|c|$, we obtain

$$(17) \quad \delta(x) = \frac{\omega_0}{2\pi} \sum_n^{+\infty} \exp[in\omega_0 x].$$

This formula is valid within any interval $T = 2\pi/\omega_0$ which includes $x = 0$. Upon substitution into (15), we get

$$(18) \quad \mathbf{A}(P, t) = \frac{e}{c\varrho} \frac{\omega_0}{2\pi} \int \mathbf{v}(t') \sum_n^{+\infty} \exp\left[in\omega_0\left(t' - t + \frac{\varrho}{c} - \frac{a}{c} \sin \vartheta \sin \alpha\right)\right] dt',$$

where the integral should be extended to a period T which includes the zero of the argument of the exponential.

But, since $v(t')$ is periodic with period T , the last condition is not necessary, and the integration can be performed over any interval T . For instance, by taking the integration variable α defined by (14) we can write

$$(19) \quad A(P, t) = \frac{e}{2\pi c \varrho} \int_{-\pi}^{\pi} v(\alpha) \sum_{-\infty}^{+\infty} \exp \left[in \left(\alpha + \varphi - \frac{\pi}{2} - \omega_0 t + \frac{\omega_0 \varrho}{c} - \frac{\omega_0 a}{c} \sin \vartheta \sin \alpha \right) \right] d\alpha$$

or

$$(20) \quad A(P, t) = \sum_{-\infty}^{+\infty} A_n \exp \left[-in \left(\omega_0 t - \varphi + \frac{\pi}{2} - \frac{\omega_0 \varrho}{c} \right) \right],$$

with

$$(21) \quad A_n = \frac{e}{2\pi c \varrho} \int_{-\pi}^{\pi} v(\alpha) \exp [in(\alpha - \beta \sin \vartheta \sin \alpha)] d\alpha$$

and $\beta = v/c = \omega_0 a/c$. It is evident that A_n represents the amplitude of the n -th harmonic of A .

6. - It is easy to see that the components of v , referred to the unit vectors of the co-ordinates at P , are given by

$$(22) \quad \begin{cases} v_\vartheta = v \sin (\omega_0 t' - \varphi) \cos \vartheta = -v \cos \alpha \cos \vartheta, \\ v_\varphi = v \cos (\omega_0 t' - \varphi) = v \sin \alpha. \end{cases}$$

Upon substitution into (21) one obtains

$$(23) \quad \begin{cases} A_{n\vartheta} = -\frac{ev}{2\pi c \varrho} \cos \vartheta \int_{-\pi}^{\pi} \cos \alpha \exp [in(\alpha - \beta \sin \vartheta \sin \alpha)] d\alpha, \\ A_{n\varphi} = \frac{ev}{2\pi c \varrho} \int_{-\pi}^{\pi} \sin \alpha \exp [in(\alpha - \beta \sin \vartheta \sin \alpha)] d\alpha, \end{cases}$$

which, by recalling formulas [4]

$$(24) \quad \begin{cases} \frac{1}{2\pi} \int_{-\pi}^{+\pi} \exp [i(n\alpha - x \sin \alpha)] d\alpha = J_n(x), \\ J_{n+1}(x) + J_{n-1}(x) = \frac{2n}{x} J_n(x), \end{cases}$$

easily yield

$$(25) \quad \begin{cases} A_{n\theta} = -\frac{e}{\varrho} \operatorname{ctg} \vartheta J_n(n\beta \sin \vartheta), \\ A_{n\varphi} = i \frac{\varrho v}{c r} J'_n(n\beta \sin \vartheta). \end{cases}$$

The radial component of $\mathbf{A}$ is negligible in the wave zone.

In conclusion, by substituting into (20) we obtain

$$(26) \quad \begin{cases} A_\theta = -i \frac{e}{\varrho} \operatorname{ctg} \vartheta \sum_{-\infty}^{+\infty} J_n(n\beta \sin \vartheta) \exp \left[-in \left(\omega_0 t - \varphi - \frac{\omega_0 \varrho}{c} \right) \right], \\ A_\varphi = \frac{e}{\varrho} \beta \sum_{-\infty}^{+\infty} J'_n(n\beta \sin \vartheta) \exp \left[-in \left(\omega_0 t - \varphi - \frac{\omega_0 \varrho}{c} \right) \right], \end{cases}$$

or, since

$$(27) \quad \begin{cases} J_{-n}(-nx) = J_n(nx), & J'_{-n}(-nx) = -J'_n(nx), \\ A_\theta = -2i \frac{e}{\varrho} \operatorname{ctg} \vartheta \sum_0^\infty J_n(n\beta \sin \vartheta) \cos \left[n \left(\omega_0 t - \varphi - \frac{\omega_0 \varrho}{c} \right) \right], \\ A_\varphi = 2i \frac{e}{\varrho} \beta \sum_1^\infty J'_n(n\beta \sin \vartheta) \sin \left[n \left(\omega_0 t - \varphi - \frac{\omega_0 \varrho}{c} \right) \right]. \end{cases}$$

We have thus evaluated the vector potential. The scalar potential is not needed, as we shall see shortly.

7. — From $\mathbf{H} = \operatorname{rot} \mathbf{A}$, we can evaluate the transversal components of the magnetic field $\mathbf{H}$. The result, which was first obtained by SCHOTT [5], is

$$(28) \quad \begin{cases} H_\theta = -\frac{1}{\varrho} \frac{\partial (\varrho A_\varphi)}{\partial \varrho} = 2i \frac{e}{\varrho a} \beta^2 \sum_1^\infty n J_n(n\beta \sin \vartheta) \cos \left[n \left(\omega_0 t - \varphi - \frac{\omega_0 \varrho}{c} \right) \right], \\ H_\varphi = \frac{1}{\varrho} \frac{\partial (\varrho A_\theta)}{\partial \varrho} = -2i \frac{e}{\varrho a} \beta \operatorname{ctg} \vartheta \sum_1^\infty n J_n(n\beta \sin \vartheta) \sin \left[n \left(\omega_0 t - \varphi - \frac{\omega_0 \varrho}{c} \right) \right], \end{cases}$$

and, since we consider the wave zone, the transversal components of the electric field will be given by

$$(29) \quad E_\theta = H_\varphi, \quad E_\varphi = -H_\theta.$$

The radial component of the Poynting vector is represented by

$$S_e = \frac{c}{4\pi} (H_\theta^2 + H_\varphi^2).$$

As is well known, its time average can be computed by adding the contributions of all the harmonics taken separately. One obtains

$$(30) \quad S_e = \frac{e^2 c}{2\pi \varrho^2 a^2} \beta^2 \sum_1^\infty n^2 [\beta^2 J_n'^2(n\beta \sin \vartheta) + \operatorname{ctg}^2 \vartheta J_n^2(n\beta \sin \vartheta)] .$$

Now we recall the series [6]

$$(31) \quad \begin{cases} \sum_1^\infty n^2 J_n^2(nx) = \frac{x^2(4+x^2)}{16(1-x^2)^{\frac{3}{2}}} , \\ \sum_1^\infty n^2 J_n'^2(nx) = \frac{4+3x^2}{16(1-x^2)^{\frac{3}{2}}} . \end{cases}$$

The validity of these formulae can be proved by power series expansion in x . They enable to perform the summation of (30)

$$(32) \quad S_e = \frac{e^2 c}{8\pi \varrho^2 a^2} \frac{\beta^4}{(1-\beta^2 \sin^2 \vartheta)^{\frac{3}{2}}} \left[1 + \cos^2 \vartheta - \frac{1}{4} \beta^2 (1+3\beta^2) \sin^4 \vartheta \right] .$$

By remembering (4), we can also write

$$(33) \quad S_e = \frac{e^4 \beta^2}{8\pi \varrho^2 m^2 c^3} \frac{\beta^2 (1-\beta^2)}{(1-\beta^2 \sin^2 \vartheta)^{\frac{3}{2}}} \left[1 + \cos^2 \vartheta - \frac{1}{4} \beta^2 (1+3\beta^2) \sin^4 \vartheta \right] .$$

By integration over a whole sphere, one would obtain exactly the expression (8) for the total power radiated. This gives us confidence in the method followed.

For small velocities ($\beta \rightarrow 0$) eq. (33) represents the classical radiation from two crossed dipoles. Maximum radiation occurs in the direction of the axis ($\vartheta = 0$). For ultrarelativistic velocities ($\beta \rightarrow 1$) the situation is completely different. A very sharp maximum of radiation occurs in the plane of the orbit ($\vartheta = \pi/2$). It is an easy matter to derive from (33) that practically all radiation is confined to an angle of the order $\sqrt{1-\beta^2}$ bisected by the orbit plane.

Eqs. (28), (29) show that in the orbit plane ($\operatorname{ctg} \vartheta = 0$) the radiation is polarized parallel to the plane ($E_\vartheta = H_\varphi = 0$).

8. - If we consider the relativistic case, we can limit ourselves to investigating radiation in the orbit plane or in its neighborhood. Let us start with $\vartheta = \pi/2$.

From (30) we have for the radiation of the n -th harmonic

$$(34) \quad S_{n\varrho} = \frac{e^2 c \beta^4}{2\pi \varrho^2 a^2} n^2 J_n'^2(n\beta) .$$

Now, since for large ν we have [7] $J'_\nu(\nu) \approx 3^{\frac{1}{2}} \Gamma(\frac{2}{3}) / 2^{\frac{1}{2}} \pi \nu^{\frac{2}{3}}$, we can approximately write for $\beta \approx 1$

$$(35) \quad S_{n_0} = \frac{6^{\frac{1}{2}}}{4\pi^3} \Gamma^2\left(\frac{2}{3}\right) \frac{e^2 c}{Q^2 a^2} n^{\frac{2}{3}}.$$

This shows that the power radiated in the orbit plane increases with increasing frequency.

However, it would be a mistake to infer that the increase shown by (35) will go on indefinitely for any high value of n . Due to the fact that β is necessarily less than unity, there will always be a value of n for which the intensity stops to increase and begins to decrease with increasing frequency. One can see this by substituting to $J_n(n\beta)$ in (34) the asymptotic expression of the Bessel function for large and nearly equal values of the order and argument [8]. When $x \approx n$ and $x < n$ the first term of the asymptotic expression can be written

$$(36) \quad J_n(x) = \frac{1}{\pi\sqrt{3}} \left(1 - \frac{x^2}{n^2}\right)^{\frac{1}{2}} K_{\frac{1}{3}} \left[\frac{n}{3} \left(1 - \frac{x^2}{n^2}\right)^{\frac{3}{2}} \right].$$

Hence, since [9] $K'_\nu(z) = -\nu K_\nu(z)/z - K_{\nu-1}(z)$ and $K_{-\nu}(z) = K_\nu(z)$, the first term for the derivative turns out to be

$$(37) \quad J'_n(x) = \frac{1}{\pi\sqrt{3}} \left(1 - \frac{x^2}{n^2}\right) K_{\frac{2}{3}} \left[\frac{n}{3} \left(1 - \frac{x^2}{n^2}\right)^{\frac{3}{2}} \right].$$

By substituting into (34) with $\beta \approx 1$, we obtain

$$(38) \quad S_{n_0} = \frac{3}{2} \frac{e^2 c}{\pi^3 Q^2 a^2} \left(\frac{n_c}{3}\right)^{\frac{2}{3}} \left(\frac{n}{n_c}\right)^2 K_{\frac{2}{3}}^2\left(\frac{n}{n_c}\right),$$

where

$$(39) \quad n_c = \frac{3}{(1-\beta)^{\frac{2}{3}}} = 3 \left(\frac{E}{mc^2}\right)^3$$

and E represents the total energy of the electron.

Since for $z \rightarrow \infty$ the asymptotic expression $K_\nu(z) = (\pi/2z)^{\frac{1}{2}} e^{-z}$ is valid [10] we see that the intensity tends to vanish for very high frequency.

The value of n for which the intensity stops to increase and starts to decrease has obviously the order of magnitude of n_c as given by (39). The frequency ($\omega_c = n_c \omega_0$), which by (5) and (39) can be written

$$(40) \quad \omega_c = \frac{3eB}{mc} \left(\frac{E}{mc^2}\right)^2,$$

is called the critical frequency (*) and specifies the spectral region in which radiation in the orbital plane is most intense. From (40) one can derive the useful numerical formula giving the critical frequency $\nu_c = \omega_c/2\pi$

$$(41) \quad \nu_{c(\text{MHz})} = 30 B_{(\text{gauss})} E_{(\text{MeV})}^2.$$

Thus, for instance, an electron traveling with the total energy $E = 5$ MeV in a field $B = 4$ G will have $\nu_c = 3\,000$ MHz, corresponding to a wavelength $\lambda_c = 10$ cm.

9. — Finally consider a direction forming a very small angle with the orbital plane, so that $\sin^2 \vartheta \approx 1 - \alpha^2$.

By putting $x = n\beta \sin \vartheta$ in (37) it is readily found that the argument of $K_{\frac{2}{3}}$ becomes now (for $\beta \approx 1$)

$$(42) \quad \frac{n}{3} (1 - \beta^2 + \alpha^2)^{\frac{2}{3}} - \frac{n}{n_c} \left| 1 + \left(\frac{n_c}{3} \right)^{\frac{1}{3}} \alpha^2 \right|^{\frac{2}{3}}.$$

The difference from the previous case is that in place of n_c we have now

$$(43) \quad n'_c = \frac{n_c}{[1 + (n_c/3)^{\frac{1}{3}} \alpha^2]^{\frac{2}{3}}},$$

i.e. a smaller critical frequency.

We therefore conclude that the frequency falls off rapidly going from the orbital plane towards the axis.

10. — The classical treatment given above is perfectly justified in all situations of physical interest. Quantum effects are negligible so long as the momenta of the photons emitted are much smaller than the momentum of the electron. For $\beta \approx 1$, the condition is $\hbar\omega \ll E$, or, substituting ω_c for ω by means of (40)

$$(44) \quad \frac{E}{mc^2} \ll \frac{m^2 c^3}{3\hbar e B} \approx \frac{2}{B} 10^{13}.$$

It is readily seen that even in a very strong magnetic field, this condition is satisfied up to enormous energies.

(*) Some authors give this name to $n_c/2$. As already pointed out, it is only the order of magnitude that matters.

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Radio-Emission from Zeta.

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A.E.R.E. - Harwell

The device at A.E.R.E. Harwell known as Zeta (Zero Energy Thermonuclear Assembly) was originally built in the hope that it would raise deuterium gas to a sufficiently high temperature to enable thermonuclear reactions to be detected. It seems at present that this hope has not been realized. Nevertheless, Zeta has provided a very high-temperature plasma which is sufficiently stable for the performance of meaningful experiments in plasma physics and it is the purpose of this note to give a brief outline of some of the results obtained.

Zeta consists of a large toroidal vacuum chamber, one metre in bore by three metres in major diameter, which forms the secondary of a large pulse transformer. The discharge usually occurs in deuterium gas at a pressure of $\frac{1}{4}$ μ m Hg and is excited by the discharge of a bank of capacitors into the primary of the transformer. Up to 500 kJ of energy is employed, (shortly to be increased to 3 MJ), and the potential round the torus ranges up to about 3 kV. A current of about 200 kA flows, the duration of the current pulse being 3 ms. This completely ionizes the gas, and the pinch effect causes the plasma thus produced to concentrate towards the centre of the tube. This also causes an increase in the longitudinal magnetic field from the applied value of about 200 G up to roughly 1500 G at the centre of the discharge.

The plasma density in some region of the discharge is probably greater than $6.3 \cdot 10^{13}$ electrons/cm³, whilst the electron temperature is in the region of a few hundred thousand degrees. It seems, therefore, that the machine has simulated a small portion of the chromosphere, or perhaps of a solar flare.

The ion temperature as given by the broadening of spectral lines appears to be a few million degrees, although it is as yet uncertain to what extent turbulent motion has affected this figure. Lines of high ionization potential are seen, derived from impurities in the gas, including C V and O VI. The discharge emits neutrons which are probably not thermonuclear in the true

sense, and also X-rays which are presumably derived from run-away electrons. Details of the configuration of the discharge are given by magnetic probe measurements and by the use of various methods of high speed photography. As yet it has not proved possible to use a Langmuir probe in the discharge due to intense arcing which rapidly destroys the probe. This arcing and general heating of apparatus placed in the discharge, together with the limited access facilities and stringent vacuum requirements tends to make plasma physics in Zeta rather a troublesome business.

One method of investigating the properties of a plasma is to use radio waves of the appropriate frequency. Electromagnetic radiation can only propagate in the plasma in the absence of a magnetic field if the frequency of the radiation is greater than the plasma oscillation frequency otherwise it will be reflected and in some circumstances absorbed. Diagnostic work on Zeta has been carried out using microwaves at two frequencies: 35 GHz ($\lambda = 8.6$ mm) and 71 GHz ($\lambda = 4.2$ mm). The critical electron densities for these two frequencies are $1.5 \cdot 10^{13}$ e/cm³ and $6.3 \cdot 10^{13}$ e/cm³ respectively. The Zeta plasma is found to be non-propagating to the 4 mm radiation in general, so that the density in some region is greater than $6.3 \cdot 10^{13}$ e/cm³. It probably rises to about $5 \cdot 10^{14}$ e/cm³ with an associated plasma frequency in the region of 200 CHz, these figures being deduced from the initial gas pressure and the pinch compression.

In theory it should be possible to investigate the spatial variation of plasma density in a stable pinch by observing the refraction of microwave radiation through it: in practice this has not yet been possible in Zeta.

So far the greater part of the microwave effort has been expended on the measurement of the radio-noise emitted by Zeta on 4.2 and 8.6 mm wavelengths. The usual problems of radioastronomy regarding receiver noise and gain stability arise, perhaps magnified by the high frequencies used. Noise factors of 15 db and 20.5 db have been achieved on 8.6 and 4.2 mm, which compare unfavorably with receivers at lower frequencies. The I.F. bandwidth used is about 3 MHz, but it is not possible to obtain high accuracy by integrating the output over long periods of time as it is necessary to be able to observe variations taking place in very short periods of time. Usually the output time-constants are between 10 and 100 μ s. Using the normal formula one obtains an error in the measured aerial temperatures of ± 500 °K and ± 2000 °K. These errors would be small if they could be compared directly with the observed aerial temperatures of a few hundred thousand degrees, but unfortunately it is necessary to attenuate the noise signal from the plasma until it equals the signal from a standard noise tube (gas discharge type) which has an apparent temperature of about 11000° at 8.6 mm and about 3000° at 4.2 mm, the latter figure being a calibration made against a hot load using a Dicke-type radiometer.

It should be pointed out that inside Zeta there will exist a plasma density gradient, the density being zero at the wall in the ideal case, and rising to its maximum value at the centre of the discharge (which is very close to the centre of the tube). Thus, just as with the Sun, whatever frequency is used will find its critical density somewhere—the higher the frequency the further into the discharge it will see, and presumably the hotter the plasma. A simplified theory proposed by A. N. DELLIS of A.E.R.E. Harwell indicated that the plasma would radiate as a blackbody in the region of the plasma frequency and hence that the microwave noise emitted would be a measure of the electron temperature at the region where the plasma frequency was equal (roughly) to the frequency being used. There appears to be some theoretical difficulty due to the penetration depth of the evanescent wave being larger than the dimensions of the apparatus, and this difficulty is still not fully resolved. It does not appear possible to obtain any appreciable optical depth if the absorption (and hence emission) is due to electron-ion collisions, which is the classical mechanism for the generation of thermal radiation. In this region also the plasma density will change considerably over one wavelength in the plasma (the refractive index is approaching zero) and the theory of the propagation under these conditions is not at all well defined. However, a small horn aerial was placed level with the wall of Zeta and the resulting output investigated.

Despite the theoretical difficulties a noise signal was received, which furthermore appeared to give temperatures agreeing with other methods. Noise temperatures up to $960\,000\text{ }^{\circ}\text{K}$ were measured and the behaviour of the noise with varying currents was as expected—the more the current in the gas, the hotter it became. It was slightly perturbing to find that the 4.2 mm results gave about half the temperature of the 8.6 mm ones, however. The radiation was not linearly polarized in any preferred direction, and did not appear to be emitted from any particular region of the plasma—a movable aerial was devised for this measurement.

The shape of the noise pulse is shown for different condenser bank voltages in Fig. 1 (8.6 mm results).

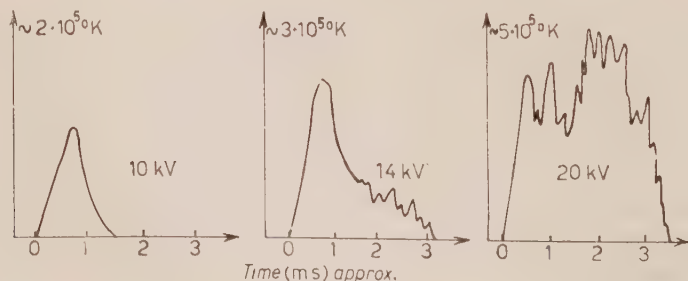


Fig. 1.

These are at a gas pressure of $\frac{1}{4} \mu\text{m}$. It will be noticed that the pulse is in two parts—an initial fairly smooth spike about 700 μs in duration, which occurs at all voltages and is very reproducible from shot to shot, and a second very irregular and quite irreproducible section which only occurs above about 13 kV, but then increases until eventually it becomes greater than the first spike at 20 kV.

At a gas pressure of $\frac{1}{2} \mu\text{m}$, the pulse is completely irregular throughout, and the observed temperatures are higher (Fig. 2). At a gas pressure of $1 \mu\text{m}$, no noise appeared under any conditions.

An experiment was performed to check the transmission of microwaves between two small aerials close to the wall of the torus. Ideally there should be no interruption of transmission as all the plasma should be «pinched» into the centre of the tube. However, it was found that transmission cut-off for 8.6 mm waves occurred during part of the pulse, and indeed the plasma near the wall was

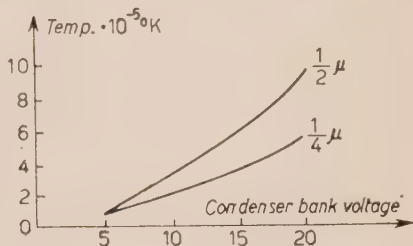


Fig. 2.

non-transmitting in general during the second part of the noise pulse. The first part of the pulse, however, should be transmitted freely. It may thus be deduced that the first peak in the noise pulse originates from the plasma and the central regions of the discharge tube, whereas the second peak comes from the stray plasma near the walls. This plasma is formed by the «boiling-off» of wall material, and might be expected to be violently turbulent. An alternative possibility is that the wall-plasma is in fact the main discharge plasma which is so violently unstable that it strikes the walls. This is thought to be unlikely, and further transmission experiments are planned at different distances into the tube to investigate which of the two possible origins for this plasma is the correct one.

The origin of this radiation is at the moment uncertain. If it is in fact thermal noise it indicates an electron temperature of about the same value as given by other methods (discharge resistivity, etc.), but perhaps slightly too high. However, there remain the theoretical difficulties discussed above.

A possibility which has very recently been considered is that the noise originates from the propagation of plasma oscillations down a density or temperature gradient. It appears that this mechanism could give the right order of magnitude of noise if a large proportion of the energy fed into the machine is used to produce plasma oscillations (TIDMAN: *Phys. Rev.*, **117**, 2 (1960)). As there is at the moment some difficulty in accounting for the disappearance of the energy by more conventional methods, this may perhaps be a worth-while

consideration. Possibly these plasma oscillations could be excited by runaway electrons.

One may conclude that the observations of radio-emission from Zeta are not yet fully understood, and one may perhaps hope that when they can be completely explained then maybe some of the problems of solar Radioastronomy will also find a solution.

INTERVENTI E DISCUSSIONI

— K. O. KIEPENHEUER:

I should like to point out that here you have a plasma which quite closely resembles a solar flare, except that the temperature may be rather high. Even the dimensions may be right about a metre across.

— D. J. H. WORT:

Yes, I had intended to point this out.

— K. O. KIEPENHEUER:

May I ask how much of the energy appears as radiation?

— D. J. H. WORT:

As far as I remember, very little. A few percent I believe — this is one of the things we hope to find out.

General Discussion on Radio-Bursts (*).

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As a starting point for this discussion the diagram was used, drawn by Dr. WILD and showing the different kinds of radiophenomena and their spectral composition, as they develop after a solar flare (Fig. 1). Each of these phenomena was successively discussed, especially in order to correlate the radio-event with physical processes in the corona. The general picture, here exposed, is the result of this combined effort by the lecturers and by the audience. Fig. 2 will help to concretize this picture.

A preliminary remark should be made, showing how difficult it is to identify the origin of a solar event. Most of the effects, due to beams of quick *corpuscles*, may be also attributed to *hydromagnetic waves*, which on their turn may have the character of transversal, longitudinal or torsional vibrations. One might think, that this ambiguity can be easily solved, since, after all, the beams, producing geomagnetic effects and solar cosmic rays are both undoubtedly corpuscular. But it seems very well possible that a longitudinal hydromagnetic wave (*S-wave*), reaching more and more rarefied layers of the corona, would gradually be transformed into a flow of gas, moving with the same velocity as the hydromagnetic wave itself and leaving the sun. The observation of corpuscular ejection therefore does not necessarily mean, that the beam had originally this character.

(*) In writing up the text of this discussion, it proved necessary to modify in several respects the conclusions of the Varenna Course. Professor KIEPENHEUER had a great share in the definitive redaction, especially as to the explanation of type II and type IV bursts.

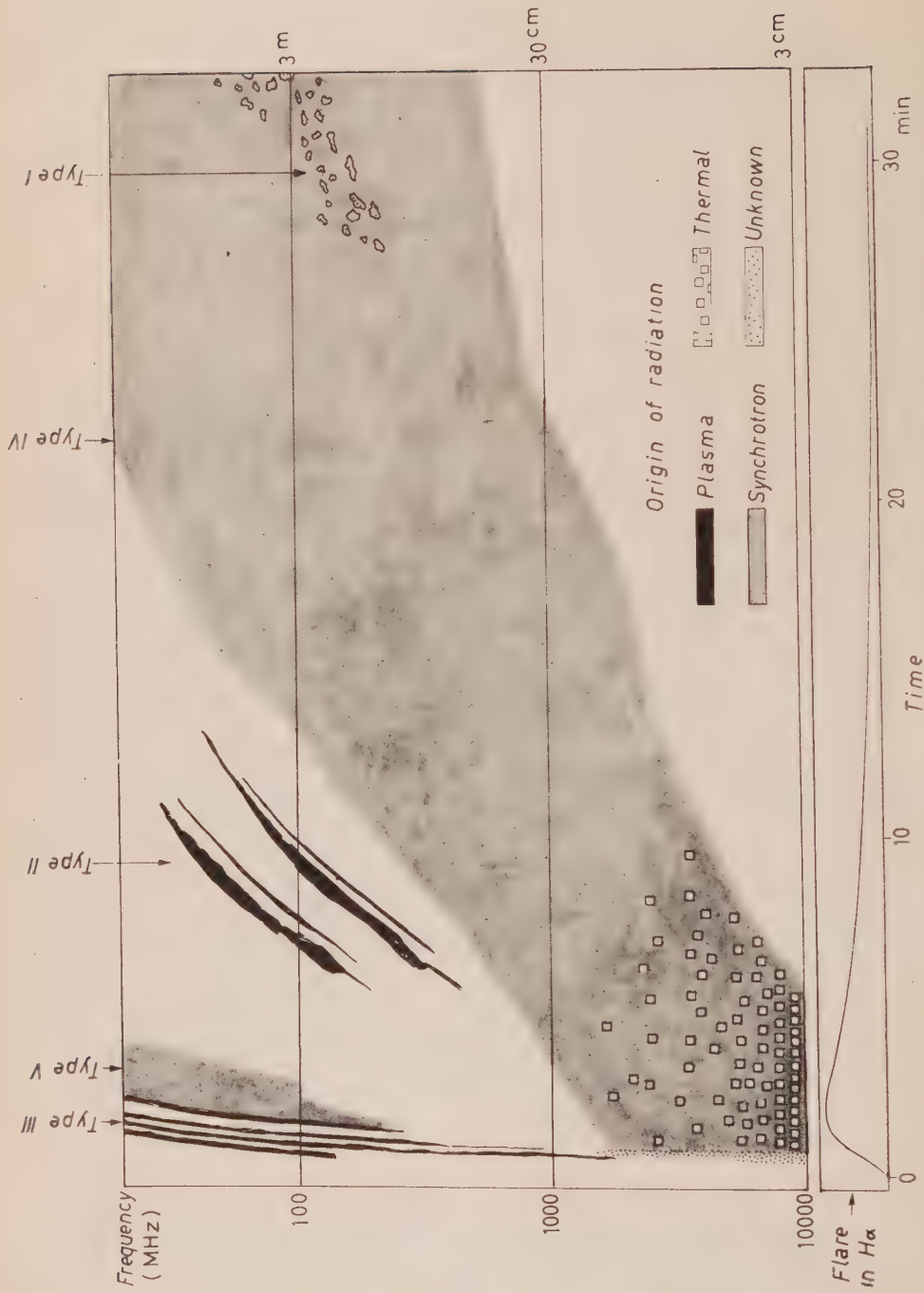


Fig. 1. - Radiospectrographic phenomena following a solar flare (P. Wind).

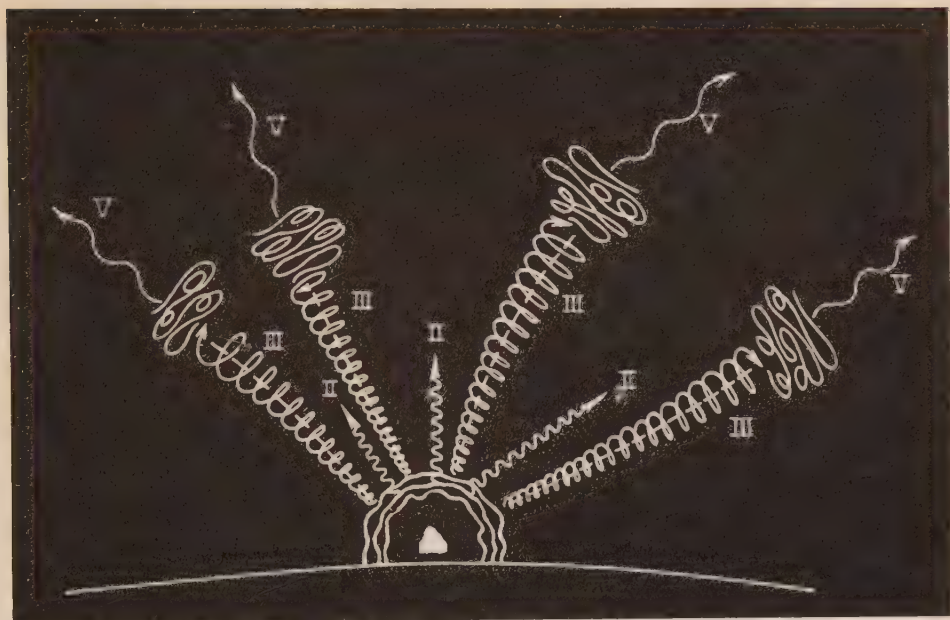


Fig. 2. — Model of radiophenomena, following a flare.

The flares.

Flares, or at least the conditions which can lead to the occurrence of a flare, are supposed to be essential for the production of all types of radio-bursts. The visible flare is very often observed as a brightening of pre-existing chromospheric facular structures; it is therefore considered to occur in the chromospheric level at a height of 10 000 km about. The observed increase of Balmer emission shows, that the hydrogen atoms are more excited than usually; this may be described as an increase of temperature, and in this way temperatures of the order of $10\,000^{\circ} \div 15\,000^{\circ}$ are currently attributed to these objects. On the other hand, the temperatures cannot be much higher, since otherwise the hydrogen would become ionized and would not radiate any more.

For the origin of this heating two theories have been recently given. Both are connected with the magnetic fields of quickly developing sunspot groups, near which flares are known to originate. 1) PIDDINGTON assumes, that hydromagnetic waves are running upwards along the magnetic lines of force (in particular torsional oscillations), and that the ions will be put into vibration by these waves; in those layers where they are intermixed with neutral atoms, the ions beat against the atoms and produce heating, excitation and radiation. 2) DUNGEY and SWEET, however, assume that the *primary flare* phenomenon takes place in the lower corona, above the *visible flare*; this primary phenom-

enon they attribute to the collision of two magnetic fields (which cannot interpenetrate), along the neutral line of the field. The squeezing effect of the two fields results in building up an extremely thin layer (thickness of a few metres) of electric currents, within which the plasma is strongly accelerated. The velocity of the electrons may easily correspond to energies of some MeV, for large flares probably even to cosmic ray energies of some GeV. Part of the particles will be shot towards the deeper chromospheric layers of the sun and can produce the visual flare in a manner similar to the production of aurorae in the earth's atmosphere, exciting the radiation of the hydrogen atoms.

Since the beam is very narrow and is produced along the neutral line of the magnetic field, the filament form of the flare is understandable.

This last point seems to us crucial for the choice between both theories. That flares preferentially occur along the neutral line, has been established by direct measurements. This seems difficult to explain by the first theory, while it is at the very basis of the second conception.

Surges.

The production of a flare is generally accompanied by the ejection of a surge moving with a velocity, smaller than or equal to the coronal velocity of sound (150 km/s). It is possible that the disruption and reconnection of the magnetic lines of force at the neutral line produce a disturbance, which becomes the origin of a cooling by thermal instability, as it occurs in prominences; the motion would be explained as the propagation of a hydromagnetic wave. On the other hand the direct observation of Doppler effects seems to show, that true corpuscular motions are involved and that matter is shot off, due to the mechanical disturbance at the point of origin.

We should remember that other explanations have been proposed for the ejection of solar clouds: the melon-seed theory (SCHLÜTER); the magnetic detention (KIPPENHAHN and SCHLÜTER); the radiation pressure.

Surges are not believed to be of direct bearing on the production of radio bursts.

In the primary flare, very high temperatures of about 10^7 degree develop. The yellow corona line is seen; and in those wavelengths where the absorption coefficient is high enough, thermal emission is produced: *a*) X-radiation, causing sudden ionospheric disturbances on earth; *b*) radio-radiation in the 3 cm range (longer wavelengths cannot escape).

Type III bursts.

From limited regions of the primary flare's current system—which seems to have a granular structure itself—some of the relativistic electrons manage from time to time to escape. They are displaced inside the cloud of positive

ions, in the same way as electrons are streaming through the crystal lattice of a metal. They are ejected in narrow beams, as separated threads, penetrating through the corona. Since they are spiralling around the lines of force of the field, their net velocity of ascension is somewhat reduced to $\frac{1}{3}c \div \frac{2}{3}c$. In the layers through which they penetrate, they excite plasma radiation, which escapes either through turbulence or through inhomogeneities, or through the action of magnetic fields. Because of diffusion and because the magnetic field decreases with height, the source of the type III burst increases its diameter with decreasing frequency, as it is confirmed by interferometric measurements. *

[PIDDINGTON proposes a different explanation: hydromagnetic transverse waves (type O or E) in the lower corona would have a velocity of 10^5 km/s, magnetic fields of 1000 G being assumed. Higher in the corona, the field will decrease, but so does the density; and the velocity of propagation, being proportional to $H/\sqrt{\rho}$, will not change much. In this theory, the travelling wave-packets are the agent which excites the radio-bursts. With these assumptions, however, the explanation of the synchrotron radiation in the concomitant type V burst seems rather difficult.]

In any explanation, a radial structure of the magnetic field is needed in order to get a normal type III burst.

Type V bursts.

Sometimes the type III event is followed by a type V burst, namely when frozen-in parts of the magnetic field are torn off and carried upward high into the corona, where normally such fields are not found. The electrons with their high velocities spiral around the lines of force and during an interval of 0.2 to 2 minutes they emit synchrotron radiation, which is observed in the radio-spectrograph. Its considerable degree of polarization shows, that the magnetic fields keep a rather-regular structure. From the spectrum, it seems that this radiation is only received when the ascending electrons have reached a rather high level; this may be understood, because the plasma frequency f_0 decreases gradually with height, whereas it is plausible that the synchrotron frequency f_c will decrease more slowly: at the moment when $f_c > f_0$, the radiation escapes.

Type II and type IV bursts.

We have now to consider several types of disturbances occurring only rarely, and which seem closely related to one and the same solar phenomenon. The

disturbances which we mean are: the triggering action of a flare on surrounding centres of activity; the radiobursts of type II; the agent producing geomagnetic storms. The main arguments pointing to their common origin are: 1) that their velocities of propagation are of the same order; 2) that there is a strong correlation between the occurrence of type II and type IV bursts with that of geomagnetic storms.

We assume that sometimes, simultaneously with the onset of a flare (or with the flash phase), a strong shock wave or hydromagnetic wave is leaving the flare region with a velocity of $(1000 \div 1500)$ km/s. This may be created by the rapid breakdown of the field along the neutral line. The propagation of such an invisible wave could explain the triggering action of a flare on other centres of activity, sometimes as far away as half the solar circumference. From the equation $H^2/8\pi = \frac{1}{2}\rho V^2$, assuming a density of 10^{-15} g/cm³ and a velocity of 1000 km/s, a field of 10 oersted is derived. This wave is propagating within the very inner corona all over the solar surface.

In regions of strong magnetic fields, that is close to sunspots, the disturbance will behave like a longitudinal (*S*-type) hydrodynamical wave, while far away from spots and high in the corona it will propagate as a pressure wave and then degenerate into a simple flow of gas with the original velocity of the wave, that is about 1000 km/s or about 7 times the coronal velocity of sound. The whole corona in these high regions may be lifted and will form an ascending cloud. The type II bursts are supposed to be emitted by plasma oscillations of the undisturbed corona, in the region where this undisturbed corona is just being hit by the disturbance. One must remember that, because of the high velocity of the wave, greater than that of sound, the density distribution in the corona remains unaltered until the very sharp shock front has arrived.

Still rarer are the cases, when a type II burst is followed by the emission of synchrotron radiation, which is recognized in the radio-sweeps by its spectral distribution and polarization. This is the type IV burst, probably emitted by the ascending coronal cloud itself. From the energy balance of geomagnetic storms (see further) it follows that the total mass of such an ejected coronal cloud should be of the order of 10^{13} g, thus relatively important in comparison with the total mass of the corona itself, which is about 10^{16} g. This means that above the flare a temporary cavity is formed in the high corona. In order to produce synchrotron radiation electrons must occur with velocities near that of light; they could be the remaining electrons of the type III burst, which are now spiralling in the high magnetic fields. In this case radiation of all higher frequencies than the plasma-frequencies is observed, apparently because the magnetic fields are stronger than in the case of a type V burst and the critical frequencies of the synchrotron radiation correspondingly higher.

Type I.

It is possible that the emission of a noise storm, designated as a type I burst, has to be considered as the last phase of the flare: in the wake of the passing shock front, high in the corona, a certain number of isolated volume elements occur where short oscillations are set up, and this goes on for a considerable time.

[However, others are of opinion that many type I noise storms have no direct connection with the flares nor with the type II-V bursts; nor is it proved that the emission is due to plasma oscillations.]

Geomagnetic storms.

Because of the similarity in the velocities, we have assumed that the hydro-magnetic wave corresponds to the agency, producing geomagnetic storms with a delay of 1-2 days. If this identification is correct, it shows that we are obliged to assume a gradual transformation of the wave into an outflow of gas. From the position on the solar disk of the flares, producing geomagnetic storms, it follows that the ejections take place in narrow beams of ions and electrons of relatively high density, directed radially. Because of the outflow, the magnetic fields have been so decreased, that the ions and electrons are released and can freely escape.

A somewhat different behaviour is shown by the plasma, producing the so called « Forbush decrease » of cosmic rays, which is considered to be modulation effect. It seems plausible, that parts of the type IV cloud are torn off, that this plasma with frozen-in magnetic fields is carried towards the earth and exercises a shielding effect on the cosmic rays coming from the universe. In this case the emission must take place in wide-opened fans of relatively small density. The rarity of the Forbush decreases corresponds with the rarity of type IV disturbances.

Cosmic rays.

Finally we have to discuss the cosmic rays proper, showing on rare occasions an increase after a strong solar flare. They are found more frequently at high altitudes, where there is less screening by the atmosphere and low energy particles are better observable. These increases have been recently considered as directly connected with the type IV event. Indeed, electrons of high velocity approaching that of light, are available among the relativistic electrons of a type IV cloud. It also sounds plausible that the ions and elec-

trons, at first spiralling around the field lines, will be set free by the expansion of the ascending cloud, the field becoming weaker and weaker till the particles escape. Very interesting is the delay of about one hour between the observation of the flare and of the cosmic ray increase. The C.R. velocities differ so little from the velocity of light, that no appreciable delay could be ascribed to this reason. Scattering in interplanetary space is excluded, since the onset is sharp in all stations. The delay, in any case, is found to depend on the latitude of the station, *i.e.* on the energy of the particles. If we assume, that the C.R. particles are released by the expansion of the ascending coronal cloud, we understand that the more energetic they are, the quicker shall they come free. At a speed of 1000 km/s already in 1000 s a height of 10^6 km would be reached; in order to explain a delay of one hour, we must assume that the fields are sufficiently weak only above $3 \cdot 10^6$ km, corresponding to two solar diameters.

It remains remarkable, that these low-energy C.R. are able to pass through the Forbush cloud, which diverts the galactic high-energy C.R. This may be understood only if the cloud is strongly turbulent and the fields are very inhomogeneous.

It cannot be denied, that this tentative picture of the successive events, following a solar flare, is still unsatisfactory and incomplete at many places. It may nevertheless incite to further discussion and create some order in the great amount of observational data.

LITERATURE ON FLARES AND CONCOMITANT EFFECTS

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Symposium Intern. Astr. Union, Nr. 6 (Stockholm, 1956). See especially the papers of: P. A. SWEET, p. 123; J. W. DUNGEY, p. 135; J. H. PIDDINGTON, p. 141; J. A. SIMPSON, p. 355.

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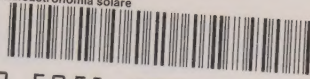
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